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Forest response to tornado disturbance and subsequent salvage logging in an East Tennessee oak-hickory forest; 14 years post-disturbance

Jonathan Charles McGrath
University of Tennessee

To the Graduate Council:

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Wayne Clatterbuck, Major Professor

We have read this thesis and recommend its acceptance:

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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and recommend its acceptance:

Dr. Jennifer Schweitzer

Dr. Callie Jo Schweitzer

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FOREST RESPONSE TO TORNADO DISTURBANCE AND SUBSEQUENT SALVAGE LOGGING IN AN EAST TENNESSEE OAK-HICKORY FOREST; 14 YEARS POST-DISTURBANCE

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Jonathan Charles McGrath
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ABSTRACT

Natural and anthropogenic disturbances are responsible for shaping forest community and structure. In February of 1993, the University of Tennessee's Forest Resources Research and Education Center in Oak Ridge, TN was hit by an F3 tornado, causing heavy damage. Subsequent salvage and slashing occurred in portions of the tornado disturbed area. This resulted in three research treatments: tornado disturbance only (tornado), tornado disturbance followed by salvage harvest (salvage), and tornado disturbance following by salvage and slashing harvest (salvage/slash). A fourth clearcut treatment of similar age from an adjacent stand was also included to compare to the tornado disturbance. The purpose of this research was to determine if treatment differences exist for measured forest stand characteristics.

In comparison of tornado, salvage, and salvage/slash treatments, importance values (IV) analysis showed treatment differences in species composition for three species (flowering dogwood, sweetgum, and Virginia pine). However, no significant difference was detected for the four most important species, yellow-poplar, black cherry, red maple, and white oaks. Tornado areas had lower species diversity (H') than other treatments in the understory and midstory, but had the greatest H' in the overstory. Non-metric multidimensional scaling (NMDS) analysis showed significant dissimilarities between treatments for four of the five strata analyzed. Tornado areas had significantly greater coarse woody debris (CWD) volume and biomass than other treatments, and salvage/slash areas had a significantly greater CWD biomass than salvage areas. No differences existed for CWD density.

In comparing the tornado and clearcut treatments, IV analysis showed differences for three species: black gum, redbud, and sugar maple. Tornado areas had greater H’ in the overstory stratum. No significant differences were detected in any other strata. CWD volume, density, and biomass were all significantly greater in the tornado areas.

Structural differences existed between natural and anthropogenic disturbances; specifically, diameter distribution and CWD loading. Due to the randomness of tornados, trees from all size classes remained standing after the disturbance. Tornado areas consisted of a more stratified vertical structure and greater CWD loads, as it was considered to be in the complex stage of stand development compared to all other treatments.

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CHAPTER 1: Introduction

Prior to human settlement, forests were shaped by natural disturbances such as fire, insect infestations, and wind events. In mesic hardwood forests of eastern United States, where humidity limits fire frequency, wind is reported to be one of the main causes of large-scale natural disturbances (Canham and Loucks, 1984). Large-scale wind-disturbance is relatively irregular in this region but can have more of a long-term effect on stand composition than smaller, more frequent single-tree blow-downs (Clinton and Baker, 2000).

On February 21, 1993 the University of Tennessee Forest Resources Research and Education Center (FRREC) in Oak Ridge, Anderson County, TN was hit by an F3 (Fujita scale) tornado. Since 1950, there have been four recorded tornadoes in Anderson County (NOAA 2007). The aforementioned tornado was most destructive tornado in the county in the aforementioned time frame. The main path of this tornado was roughly 10 miles (16.1 km) long, 0.45 miles (0.72 km) wide, and irregularly shaped (Newbold 1996). On the FRREC, 249 acres of forest were heavily damaged by the tornado and 103 acres had light to moderate damage, totaling roughly 352 acres of damage.

Due to the moderately infrequent and unpredictable nature of tornadoes and large-scale wind disturbances in the ridge and valley region, there is little work examining the successional pattern following such disturbance. Furthermore, most of the studies in the eastern United States do not explore the effects of salvage logging after tornado disturbance (Peterson and Pickett 1995; Arevalo et al. 2000; Peterson and Rebertus 2000). The tornado disturbance site at the FRREC provides a unique opportunity to evaluate vegetation development following different disturbances. Because vegetation response to large-scale wind disturbance is unpredictable and no predictive outline has yet been created (Peterson and Pickett 1995), I evaluated the vegetation and coarse woody debris (CWD) response of tornado disturbance compared to forest management operations implemented as post-tornado mitigation. The treatments examined in this research are:

- Tornado (T) – tornado disturbed, no post-tornado harvest
- Salvage (S) – tornado disturbed, salvage harvest with only merchantable material removed
- Salvage and Slash (SS) – tornado disturbed, salvage harvest followed by slashing of all standing material 2 inches (5.1 cm) DBH and above

In addition to the three treatments listed above a fourth clearcut (CC) treatment will be compared to the tornado disturbance only (T) to evaluate differences and similarities between natural and anthropogenic disturbances.

Objectives

Fourteen years after the tornado damage and roughly 13 years after salvage treatments, vegetation and CWD data have been collected and used to meet the following objectives:

1. Evaluate the impacts of tornado disturbance and subsequent salvage harvests on stand characteristics, including species composition and diversity, diameter distribution, and density.
2. Assess the impacts of tornado disturbance and subsequent salvage harvests on CWD density, CWD volume, and CWD biomass.

3. Compare natural and anthropogenic disturbances by examining stand characteristics of a clearcut harvested in a timeframe similar to the tornado and comparing it to the tornado-disturbance area.

The overall objective of this study is to be able to provide information that may aid management decisions for tornado-disturbed forest stand. These management implications are not strictly limited to attaining silvicultural goals, but ecological and wildlife-oriented goals as well. This thesis will address the following questions:

- Which treatment(s) are adequately stocked with desirable tree species?
- Which treatment has the highest woody and herbaceous species diversity?
- Which treatment provides the most structural diversity for wildlife?
- Which treatment provides the highest levels of coarse woody debris for habitat?

The objectives listed above were met by testing a null hypothesis that all treatments are not significantly different from each other for a given stand characteristic. The alternative hypothesis is that the treatments are significantly different for a given stand characteristic. Stand characteristics that were evaluated are species composition and diversity, diameter distribution, stem density, and CWD density, volume and biomass.

CHAPTER 2: Review of the Literature

Susceptibility

Many factors have been attributed to a stand's susceptibility to wind-disturbance. Stand age has been linked to the stand's vulnerability to damage. As hardwood stands approach 80 years old, they become more likely to suffer severe damage (Evans et al. 2007; Foster 1988). Tree size and species also have an effect on level of wind damage in eastern and central forests (Foster 1988; Webb 1989; Peterson and Pickett 1991, 1995; Peterson and Rebertus 1997; Kuers and Grinstead 2006). Slope position appears to have an effect on tree susceptibility to windthrow. Damage from Hurricane Opel was shown to occur more on ridges and upper-slope positions, due to shallow soils saturated by the storm and the high leaf area of the large crowns on older trees (Clinton and Baker 2000).

Species Richness

Among other factors, storm intensity can alter overall species richness. In comparing two tornadoes of different intensities in old-growth forests in Tionesta, Pennsylvania, Peterson (2000) reported that size and intensity of tornadoes play a large role in initial stand damage as well as stand recovery. In comparing an F4 and an F1 tornado, Peterson documented that more intense wind events resulted in lower initial post-storm basal area but greater woody species diversity whereas smaller storms retained constant species diversity when compared to an intact forest. This coincides with findings by Runkle (1982) and Clinton et al. (1994) that showed species richness increases with increasing gap size. They also found richness is highest two years after the creation of gaps and begins to decrease over time.

After a straight-line wind disturbance in an oak forest in Minnesota, no significant change in the diversity of woody species were detected (Arevalo et al. 2000). Peterson and Rebertus (1997) observed a significant decrease in canopy tree diversity after an intermediate intensity tornado due to the loss of species from blow-down of canopy trees. In the same study they found herbaceous species richness to be similar between upland, lowland, and swamp sites following tornado disturbance.

Few studies have examined the difference in species diversity between tornado disturbance and tornado-disturbed salvaged areas. In an F4 tornado in bottomlands of southern Illinois, no significant difference in woody or herbaceous species richness was reported between wind-disturbed stands and those that were salvaged following the disturbance. Woody species diversity appears to differ between undisturbed stands and wind-disturbed or salvaged stands (Nelson 2007).

Regeneration and Recovery

Large-scale wind disturbance would be expected to alter stand basal area and stem density and generally increase with gap size (Runkle 1982). In a central Minnesota oak forest, Arevalo et al. (2000) reported stand basal area had an initial drastic drop and then a steady increase, reaching roughly 80% of the initial basal area within 14 years. Stem density followed a slightly different pattern. Immediately following the storm, stem density declined as did basal area. However, the number of stems per acre quickly increased to a point above the initial stocking level, and continued to increase. Nelson (2007) reported that woody regeneration stem densities over three years post-wind disturbance were not significantly different than stands that were subsequently salvaged. Undisturbed stands, however, showed significantly lower mean stem densities. Similar trends were observed in overstory species regeneration stem densities.

The intensity of wind disturbance is a determining factor in regeneration of the future stand. Peterson and Rebertus (1997) noted that over half of the trees surveyed greater than 6 inches (15 cm) in an oak-hickory disturbed by an "intermediate" tornado resprouted in some way. Ninety percent of those sprouts were epicormic sprouts. Peterson (2000) indicated that in more destructive windstorms, sprouting is less of a contributor of the future stand than in lower intensity storms. The size of the stem also has an influence on the sprouting potential after a storm, where a site with smaller stems is more likely to have sprouts contribute to the main canopy. Seedlings may be more likely to fill larger gaps created by higher intensity wind-disturbances. When smaller gaps are created more diverse mechanisms of regeneration take place such as sprouting, releasing of advanced regeneration, and establishment of new seedlings. In the case of smaller gaps, new seedlings play less of a role in the future stand (Peterson 2000).

Sprouting, both stump and epicormic, are an important means of recovery and persistence on a landscape. Stump-sprouts grow vigorously and can often out-compete seedling regeneration. Most young hardwood stands contain and can be completely developed from stump-sprouts (McGee et al. 1979). In 12 year-old clearcuts, Lamson (1983) observed that the average height of sprout-origin black cherry (*Prunus serotina*), yellow-poplar (*Liriodendron tulipifera*), red maple (*Acer rubrum*), and northern red oak (*Quercus rubra*) were 37 feet (11.2 m) tall, and that seedling-origin black cherry and yellow-poplar averaged a height of 30-35 feet (9.1-10.7 m) (Lamson and Smith 1989). This indicates that sprout-origin regeneration has a height advantage over other regeneration sources, grows faster and will compose a major portion of the future stand due to the already intact root system.

Clinton et al. (1994) reported species with a diversity of shade tolerance levels were present in smaller gaps, similar to the edge of a tornado path. Furthermore, densities of typical gap species such as yellow-poplar and northern red oak were found to generally increase with increasing gap size. Webb (1989) found shade intolerant species are more likely to appear in large gaps, but observed little diversity in shade tolerance in smaller gaps. Shade tolerant, "wind-hearty" species are more likely to be found in smaller gaps. Black gum (*Nyssa sylvatica*) and red maple are two shade tolerant species found in moderate (0.2 to 1.1 hectare) gaps due to their resistance to wind (Greenberg and McNab 1998).

Succession

Price et al. (1998) examined stands 60-80 years old that originated from either clearcutting or wind-disturbance, comparing structural and ecological differences. A key structural finding was that two of the three wind-disturbed stands showed the negative exponential diameter distribution similar to a diameter distribution found in the complex stage of development. Although these stands did not have large diameter trees similar to some old-growth stands, the diameter distribution (with smaller diameter trees) coupled with gap dynamics and the number of snags resembled the structure of a complex-stage forest.

Post-wind-disturbance logging operations influence successional trends. According to Spurr (1956), the new stand after hurricane wind-disturbance, absent of logging, is "a late-successional association composed of the released understory trees". Stands with subsequent logging after wind damage consist of released understory species intermixed with pioneer species that had seeded into the area.

Coarse Woody Debris (CWD)

Large amounts of CWD are added to forest floor after windthrow from tornadoes and are an important source of nutrients as well as habitat for wildlife. Wind is reported to be one of the major agents of mortality in temperate forests (Harmon et al. 1986). Mattson et al. (1987) observed highest accumulation of coarse woody debris immediately following disturbance. After natural disturbances like tornadoes, new, post-disturbance CWD has been found to significantly add to accumulation of pre-disturbance CWD, causing a large CWD buildup after natural disturbance (Van Lear 1996). These disturbances have shown CWD levels higher than normal gap-phase dynamics of uneven-aged stands (Hook et al. 1991; Myers et al. 1993).

A number of studies have reported the importance of coarse woody debris to forest dwelling birds, mammals, and herpetofauna. In a synopsis on the relationship between coarse woody debris and bird communities, Lanham and Guynn, Jr. (1996) outlined numerous studies that document the importance of CWD on southeastern forest inhabiting birds. Loeb (1996) also outlined a number of studies that noted the importance of CWD on southeastern mammal communities. Log piece size and decay condition were key characteristics of a log that determined its use by most vertebrate species. In general, larger diameter, less decayed log pieces are more useful to wildlife than smaller, highly decayed pieces (McComb 2008).

CHAPTER 3: Study Site

The University of Tennessee Forest Resources Research and Education Center (FRREC) is located in Oak Ridge, TN in Anderson County (Figure 3.1). The FRREC is a 2,260-acre (915-ha) tract that is part of the University of Tennessee Agricultural Experiment Station. The FRREC is found in the ridge and valley physiographic province, which is characterized by long, parallel, northeast-southwest running ridges that create narrow valleys between them (Moneymaker 1981).

Average annual precipitation for Oak Ridge is 55.1 inches (140.0 cm), 11.1 inches (28.2 cm) from snowfall. Average monthly temperatures range from 57.2° F (14° C) to 77.3° F (25.2° C) during spring and summer growing season months (April through September) (NOAA 2008). Soils within the research area are in the Fullerton series and are described as very deep, well-drained cherty silt loam soils. These soil types have slopes ranging from 5% to 45% (NRCS 2007). The average slope in the study area is 22.5% (research data).

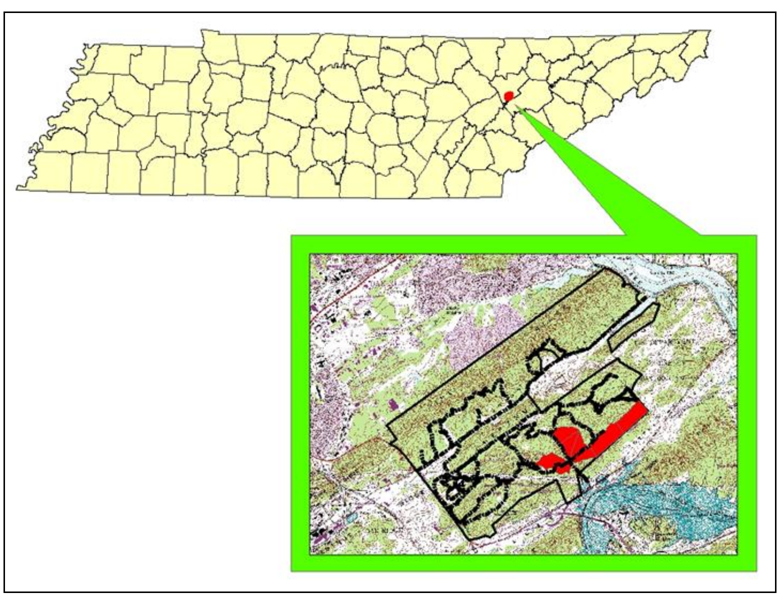


Figure 3.1: FRREC property boundary and thesis research area in Oak Ridge, Anderson County, Tennessee

In February 1993, an F3 tornado impacted the FRREC with maximum wind speeds of 158-206 mph (254-332 kph) (City-Data.com 2007). The tornado was limited to Chestnut Ridge portion of the FRREC and caused extensive levels of windthrow on roughly 350 acres (142 ha). As part of Karen Andreadis's (1995) and Chris Newbold's (1996) thesis projects, three treatments were implemented to evaluate small mammal and avian communities, respectively, and their usage of post-disturbance habitats. The three treatments at the tornado site were: salvage and slash all standing timber (SS1 and SS2; 19 and 37 acres respectively), salvage with no slashing (S1 and S2; 16 and 30 acres respectively), and tornado-disturbance only with no harvesting (T1 and T2; 31 and 28 acres respectively) (Figure 3.2).

A fourth clearcut treatment was used to compare anthropogenic and natural disturbances. The clearcut was part of a site preparation study conducted in 1989 (Andrews 1995) to determine the most efficient way to regenerate a mixed pine-hardwood stand. The four treatments were silvicultural clearcut, silvicultural clearcut followed by burning, silvicultural clearcut followed by herbicide application then burning, and commercial clearcut. Treatments were broken into 1-acre (0.4-ha) blocks, replicated five times (Figure 3.3). Following site preparation, all treatments were planted with eastern white pine (*Pinus strobus*) and loblolly pine (*Pinus teada*) seedlings on a 20 x 20 foot (6.1 x 6.1 m) spacing, totaling 100 trees per acre (247 trees per hectare).

For the purpose of this research, only silvicultural clearcut blocks were assessed. Seedling survivorship for white pine and loblolly pine were 55% and 70%, respectively, one year after planting. Since then, the component of planted pine is negligible. The only remaining individuals are along replicate block edges, outside of vegetation and coarse woody debris plots of this study (see Chapter 5 - Methods).

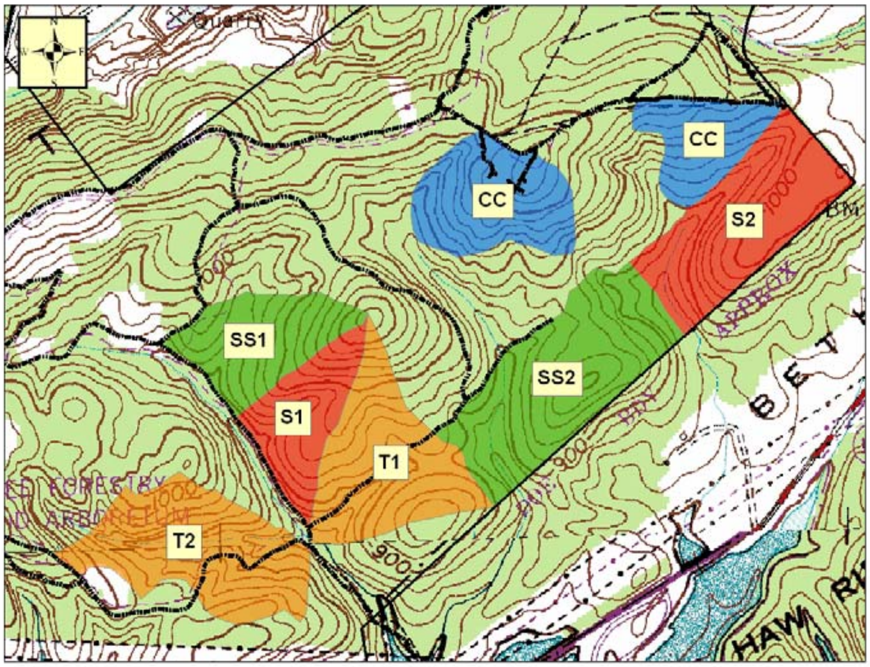


Figure 3.2: Treatment areas: Tornado (T1and T2) in orange; Salvage (S1 and S2) in red; Salvage/slash (SS1 and SS2) in green; and clearcut in blue at the FRREC in Oak Ridge, TN.

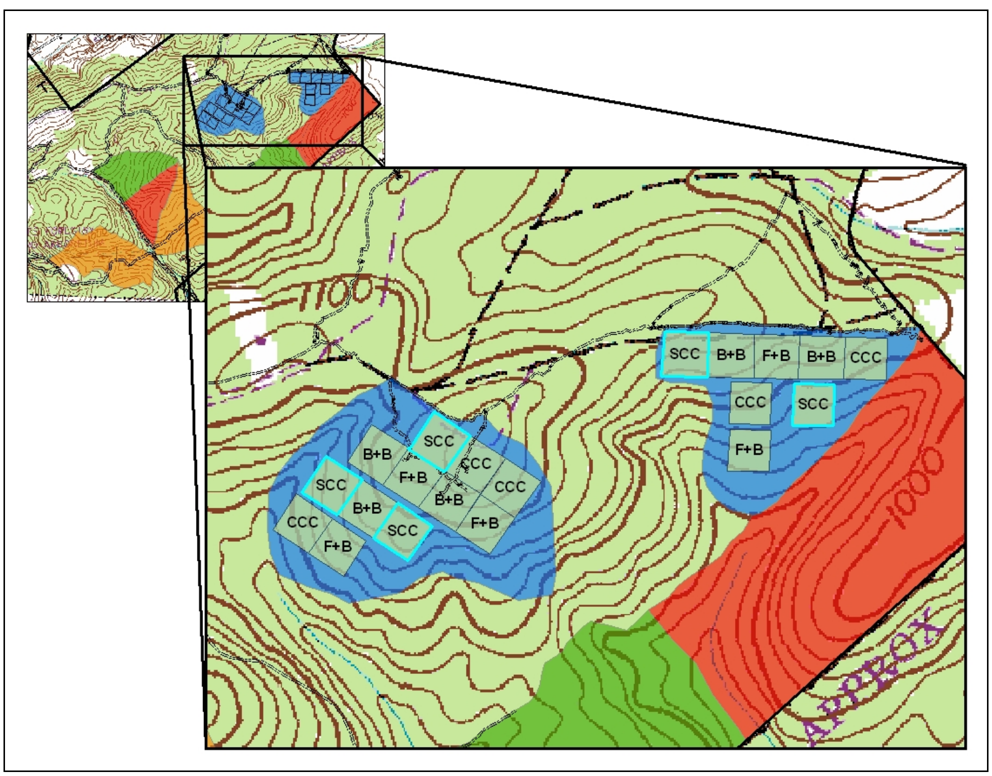


Figure 3.3: Clearcut blocks from 1989 site preparation study: SCC (silvicultural clearcut); F+B (fell and burn); B+B (brown and burn); CCC (commercial clearcut) at the FRREC in Oak Ridge, TN. SCC blocks are highlighted in light blue.

No pre-disturbance inventory was conducted on the tornado-disturbance study area. However, Newbold (1994) cited the pre-disturbance stand as a two-aged oak-hickory forest. The two age classes consisted of a 100-120 year old cohort of mostly oak species and a 60-80 year old cohort that consisted of a significant amount of yellow-poplar. Timber cruises and pre-harvest inventories conducted in surrounding stands prior to tornado disturbance also indicate that the study area was an oak-hickory forest. More specifically, the stand was dominated by red oak species (mainly *Quercus rubra*), white oak (*Quercus alba*), and chestnut oak (*Quercus prinus*). Inventories indicate that yellow-poplar, hickory (*Carya spp.)* and miscellaneous hardwood and pine species also existed within the stand, but to a lesser extent than the oak species.

CHAPTER 4: Vegetation Response to Tornado Disturbance and Subsequent Salvage and Salvage/Slash Logging

METHODS

Vegetation

Beginning in August 2007, vegetation data were collected across all tornado-disturbed areas. Study areas were laid out in the spring of 1994 and followed a complete randomized design. Within each treatment, two treatment areas were established at this time (see Figure 3.2). Variability exists between treatment areas, within a single treatment, due to different slope positions, aspects, and, primarily, level of disturbance caused by the tornado. Although this variability exists, most analysis has been conducted at the treatment level. Pseudoreplication occurs as each plot is statistically treated as a replicate considering low number of true replicates resulting in low statistical power. The assumption of true replication in the complete randomized design is admittedly not satisfied because natural disturbances such as tornadoes cannot be replicated.

Plot setup was as follows: Twelve to 14 plots were established in each of the six tornado-disturbed study areas (2 tornado, 2 salvage, 2 salvage/slash) with a treatment total ranging from 24 to 27 plots in each treatment (Figure 4.1). Each treatment area was systematically laid out with a series of transect lines connecting plots, with a random starting point. Due to varying treatment area size across the six tornado-disturbed areas, plot spacing varies across areas, but is uniform within each area. Plots landing on a skid trail, road, old log landing or treatment area boundary were moved one chain (66 feet or 20.1 m) perpendicular to the transect line away from the obstruction.

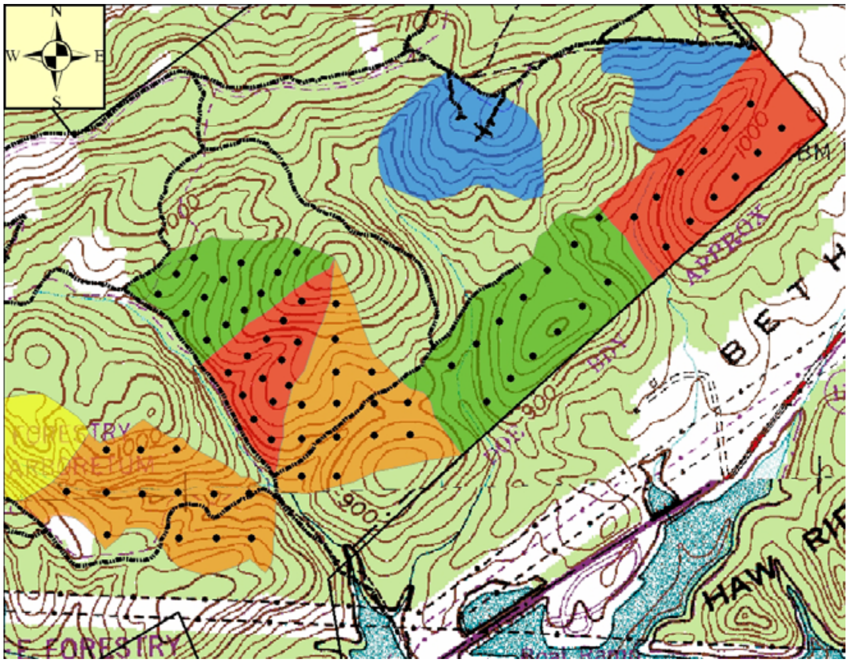


Figure 4.1: Vegetation/CWD plot layout on Tornado (orange), Salvage (red) and Salvage/Slash (green) treatment areas at the FRREC in Oak Ridge, TN.

At each plot, three nested, fixed-area plots were established to measure the: overstory, midstory, and understory. Percent slope, aspect, and slope position were recorded at the center stake of each plot. Percent slope was assessed using a Suunto clinometer. Aspect was categorized as being one of the four cardinal directions or a midpoint between two of the four cardinal directions (i.e. N, NE, E, SE, etc.). Slope position was classified as being on the upper, middle or lower third of the slope. These data were used as explanatory variables for variability between plots within treatments.

Each vegetation plot was broken into 5 strata categories:

- Overstory vegetation
- Midstory vegetation
- Understory woody vegetation greater than 4 feet (1.2 m) tall
- Understory woody vegetation less than 4 feet (1.2 m) tall (presence/absence only)

- Understory herbaceous vegetation (presence/absence only)

Tenth acre (0.04 ha) overstory plots were centered along the predetermined transect line. At each overstory plot, trees with a diameter at 4.5 feet (1.4 m) from the ground (DBH) greater than or equal to 4.5 inches (11.4.cm) were tallied, and species and DBH were recorded for each tree. DBH was measured by one-inch diameter classes where the i^{th} inch-class ranged from [*i*-1].5 to [*i*].4. Midstory plots were 0.02 acres (0.008 ha) with the same plot center as the overstory plot. At each midstory plot, trees from 1.5 to 4.4 inches (3.8 to 11.2 cm) DBH were measured and recorded by species and diameter class. Two understory plots were measured at each overstory plot. The center of each of the two plots was 0.33 chains (6.7 m) perpendicular to and on either side of the transect line. The plots measure 0.001 acres (0.0004 ha) and every woody stem measuring less than 1.5 inches (3.8 cm) DBH was recorded. Woody stems with a height greater than or equal to 4 feet (1.2 m) were tallied by species. All woody plants less than 4 feet (1.2 m) as well as herbaceous plant species were recorded by species.

Coarse Woody Debris

In the spring of 2008, coarse woody debris (CWD) was evaluated using the line intersect method, described by Waddell (2002). For every downed tree along a transect line, diameter at large and small end and length were measured. CWD measurement parameters include density, volume, and total biomass based on formulas derived from De Vries (1973) and presented by Waddell (2002) and Woodall and Monleon (2007). All of the following methods for CWD data collection are based on Waddell (2002).

CWD plots were placed at the same plot location as each of the 87 vegetation plots. Each plot contained three transect lines, 37.2 feet (11.3 m) long, from the center of the circular plot. Transect lines were oriented at 0, 135, and 225 degrees. Transect lines were traversed and a piece of CWD was measured if (Figure 4.2):

1. the central longitudinal axis of the piece intersected the transect
2. the diameter at the point of the intersections was at least 5 inches (12.7 cm)
3. the piece length was at least 3.3 feet (1 m)
4. the piece was not decayed to the point of having no structural integrity

In situations where large limbs from the main bole of the tree intersected the transect line or a tree forks and both forks crossed the transect line, they were treated as two separate pieces (Figure 4.3). In this instance, the larger diameter stem was considered the main bole of the tree and smaller segment(s) were measured to the main bole as a separate piece.

For each CWD piece crossing the transect line, diameter at the large end and small end, and the total length were measured, and a decay class of 1-5 was assigned to each CWD piece (Waddell 2002, Table 1). Cubic foot volume for a single CWD piece was first calculated using the following equation:

$$\text{Volume of a log: } V_{\text{ft}} = [(\pi/8)(D_S^2 + D_L^2)l]/144$$

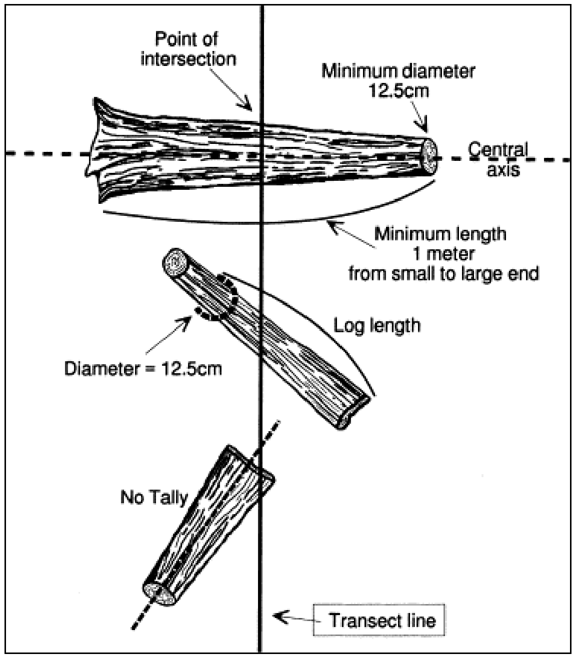


Figure 4.2: Log measurement requirements for those intersecting the transect line (from Waddell 2002, Figure 2) in the tornado disturbance treatments at the FRREC in Oak Ridge, TN.

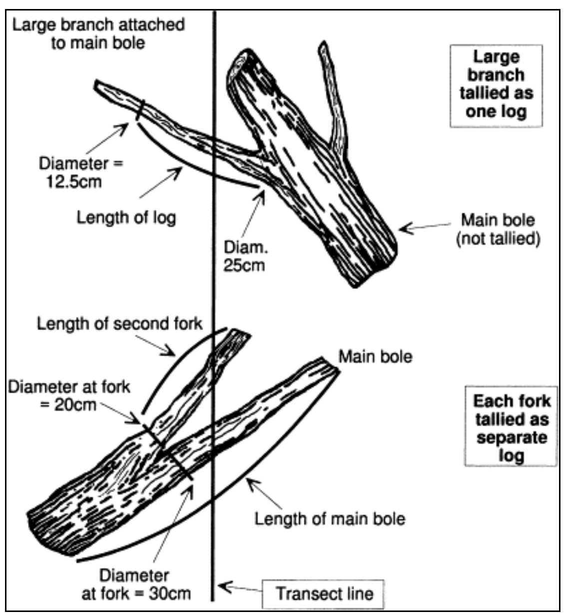


Figure 4.3: Log measurement requirements for forked or branched logs (from Waddell 2002, Figure 3) in the tornado disturbance treatments at the FRREC in Oak Ridge, TN.

where V_{ft} is the volume (ft^3), D_S is the small-end diameter (inches), D_L is the large-end diameter (inches) and l is the piece length (feet). Per-unit-area attributes were computed based on De Vries's (1973), Waddell's (2002) and Woodall and Monleon's (2007) formulas:

$$\text{Volume } (ft^3/\text{acre}) = (\pi/2L)(V_{ft}/l_i)f$$

$$\text{Density (logs/acre)} = (\pi/2L)(1/l_i)f$$

$$\text{Biomass (tons/acre)} = (1/2000)*[(\pi/2L)(V_{ft}/l_i)f]*BD*DC$$

where f is the per-unit-area expansion factor (43,560 ft^2/acre, 10,000.m^2/ha), L is the transect length (37.2 feet, 11.3 m), BD is the bulk density of hardwood (28.7 lbs/ft^3, 459.7 kg/m^3) (Woodall and Monleon 2007, Appendix 7.3), and DC is the decay-reduction constant (Table 4.1). Because species group was not recorded during data collection and most of the tree composition at the time of the storm was in the hardwood species, hardwood decay-reduction constants were used.

Table 4.1: Decay-reduction constants for CWD pieces by species group (from Waddell 2002, Table 4) in the tornado disturbance treatments at the FRREC in Oak Ridge, TN

	Species Group	
Decay Class	Softwood	Hardwood
1	1.00	1.00
2	0.84	0.78
3	0.71	0.45
4	0.45	0.42
5	0	0

Data Analysis

Upon completion of data collection, vegetation and CWD data were analyzed for multiple stand and community characteristics. Species evenness (H') was calculated for woody vegetation greater than 4 feet (1.2 m) tall, midstory, overstory, and combined midstory/overstory, using the Shannon Index (Shannon 1948).

Midstory and overstory density and basal area were calculated. Overstory and total basal area were reported for each treatment with associated stand errors to evaluate variability within treatments. Relative density and relative dominance (basal area) were calculated to determine species importance values (IV's). Relative frequency was omitted from the standard IV calculation (Curtis and McIntosh 1951). If included, it would have caused bias based on the low abundance of many species in the overstory strata and spatial variability associated with the tornado disturbance. Therefore, the total IV summation index was calculated out of 200 instead of 300. Midstory and overstory IV's were calculated as separate strata, then together to determine species importance of all trees 2 inches (5.1 cm) and greater in diameter. Black oak (*Quercus velutina*), scarlet oak (*Quercus coccinea*) and northern red oak were grouped together as "red oaks", chinquapin oak (*Quercus muhlenbergii*), chestnut oak and white oak were grouped as "white oaks", and red elm (*Ulmus rubra*), winged elm (*Ulmus alata*) , and American elm (*Ulmus americana*) were grouped as "elms".

Once IV's were calculated, species scoring less than 4.0 were dropped from the analysis. This value was selected because there was a natural break in the dataset, where species scoring less than 4.0 were usually observed on a single occasion within a given treatment. The five species with the highest IV's for each treatment were then used in diameter distribution curves and species density tables.

All statistical analyses were performed to test the null hypothesis, stating that there is no significant difference between treatments. To test this, a Mann-Whitney analysis (Mann and Whitney 1947) was computed where plot means were ranked and an ANOVA was performed on the rank to determine statistical significance between treatments. Shannon (H') index scores, importance values and CWD volume, density, and biomass were all tested in this manner by treatment.

Non-metric multidimensional scaling (NMDS) analyses of changes in vegetation community composition were conducted using PRIMER-E statistical package (Minchin 1987, Clarke and Warwick 2001). The major directions of plant community compositional change was assessed between treatments and treatment areas at each of the five strata levels. Herbaceous and woody vegetation less than 4 feet tall was based on species presence/absence. Woody vegetation greater than or equal to 4 feet, midstory trees and overstory trees were based on species abundance. A dissimilarity matrix of the plant communities collected from each treatment was calculated using the Bray-Curtis dissimilarity coefficient (Legendre and Legendre 1998). An analysis of similarity (ANOSIM) was used to test for statistical differences between treatments and treatment areas. Pairwise tests were conducted between all possible treatment and treatment area pairs using 999 permutations. X,Y scatter plots were created based on the Bray-Curtis similarity matrix using SigmaPlot 10.0 (Systat Software Inc., San Jose, CA).

Hypotheses

Based on different harvesting methods in each treatment and personal observation, I hypothesize that the diameter distributions will be different between treatments. The expectation is that the tornado areas will have a highly skewed distribution from the normal even-aged distribution because many residual large diameter trees remained (standing) after the tornado. The salvaged areas are anticipated to have a less skewed distribution than the tornado areas, but more skewed than the salvage/slash areas, because some residual, non-merchantable trees were left following the salvage harvest. Furthermore, overall tree density is hypothesized to be highest in the salvage/slash treatment followed by salvage and then tornado. For all CWD attributes significant differences between treatments are expected. Since no material was removed from the tornado areas, these areas are predicted to have the highest amount of CWD. Salvage/slash areas are predicted to have more CWD than the salvage treatments because non-merchantable trees were cut and left on site.

RESULTS

Variability

Total basal area and the associated errors were similar between salvage and salvage/slash treatments (Table 4.2). However, the tornado treatment had a greater overall basal area and a standard error nearly twice that of the salvage and salvage/slash. Overstory basal area was 2.5 times greater in the tornado treatment than the salvage treatment and over 4 times that of the salvage/slash. The greater standard error for the tornado treatment illustrates the high variability in that treatment.

Table 4.2: Overstory and total basal area calculations for Tornado (T), Salvage (S), and Salvage/Slash (SS) treatments at the FRREC in Oak Ridge, TN.

	T S		SS
Overstory			
Mean BA (ft^2/acre)	63.30	25.93	14.84
Standard Error	7.20	2.69	2.01
Total			
Mean BA (ft^2/acre)	90.11	63.83	58.51
Standard Error	6.05	3.21	2.51

Importance Values

Sixteen species/species groups had an importance value greater than 4.0 in one of the three treatments. Of those sixteen species only three species showed significant differences ($\alpha = 0.05$) between the three treatments: flowering dogwood (*Cornus florida*), sweetgum (*Liquidambar styraciflua*), and Virginia pine (*Pinus virginiana*). Although the elm species group appears to show significance in the mean separation test (Table 4.3), no significant treatment difference was found in the F-test. On average, yellow-poplar, red maple and black cherry were the most important species across all treatments. White oaks were more important than red oaks for all treatments.

Although not statistically significant, the red and white oak groups, black gum, and red maple all have greater IV's in the tornado treatment compared to the salvage and salvage/slash treatments (Figure 4.4). This is similar to the significant result found with flowering dogwood. Conversely, yellow-poplar and redbud (*Cercis canadensis*) have much greater IV's in the salvage and salvage/slash treatments compared to the tornado.

Tree Density and Structure

Using the 2-inch to the 33-inch diameter classes, all diameter distribution curves are relatively similar in shape (Figure 4.5-A). Under closer investigation, Figure 4.5-B shows

Table 4.3: Importance values by species based on a maximum 200 possible value in the tornado disturbance treatments at the FRREC in Oak Ridge, TN. P-values are reported for the overall model (signifies p ≤ 0.05). Different letters signify statistically significant differences between treatments using least significant differences. See Appendix for species codes and names.*

species	**Tornado Sa**		**lvage**		**Salvage/Slash**		p-value
BLCH	24.03	A	21.83	A	24.13	A	0.6484
BLGU	7.95	A	3.75	A	3.83	A	0.1798
DOWO*	10.18	A	3.04	B	2.62	B	0.0005
Elms	0.58	B	2.63	AB	5.31	A	0.0727
HICK	5.88	A	6.69	A	4.93	A	0.5704
Red Oaks	9.56	A	6.27	A	5.55	A	0.6142
REBU	7.31	A	16.84	A	15.36	A	0.6114
REMA	38.34	A	25.09	A	24.68	A	0.1506
SASS	3.03	A	11.50	A	6.45	A	0.1442
SOWO	14.28	A	12.02	A	12.41	A	0.7103
SUMA	4.16	A	2.93	A	2.15	A	0.233
SWGU*	0.39	B	4.18	A	0.32	B	0.0168
VIPI*	1.08	B	2.10	B	8.43	A	0.0002
White Oaks	21.33	A	13.20	A	13.59	A	0.1127
WHPI	4.68	A	2.91	A	0.21	A	0.2303
YEPO	38.09	A	53.65	B	55.45	AB	0.0801

that salvage and salvage/slash diameter distribution curves are more similar in shape, having a large number of trees in the 2- to 4-inch classes. Conversely, the tornado distribution has fewer trees in the smaller diameter classes and more trees in diameter classes 4 inches and greater compared to the other two treatments. More structural diversity can be seen in the larger diameter classes in the tornado treatment compared to salvage and salvage/slash treatments (Figure 4.5-C). No trees greater than 11 inches were observed in the salvage/slash treatment and no trees greater than 19 inches were observed in the salvage treatment. The largest diameter tree observed in the tornado treatment was 33 inches.

In the salvage treatment, yellow-poplar has the greatest density in the 2- to 10-inch classes (Figure 4.6-A) as well as the greatest overall density (Table 4.4-A). Yellow-poplar, red maple, and white oak are the only species that exist in 10-inch and greater diameter classes. Although black cherry and redbud do not appear in those aforementioned diameter classes, the overall density of those species is greater than the white oak group (Table 4.4-A).

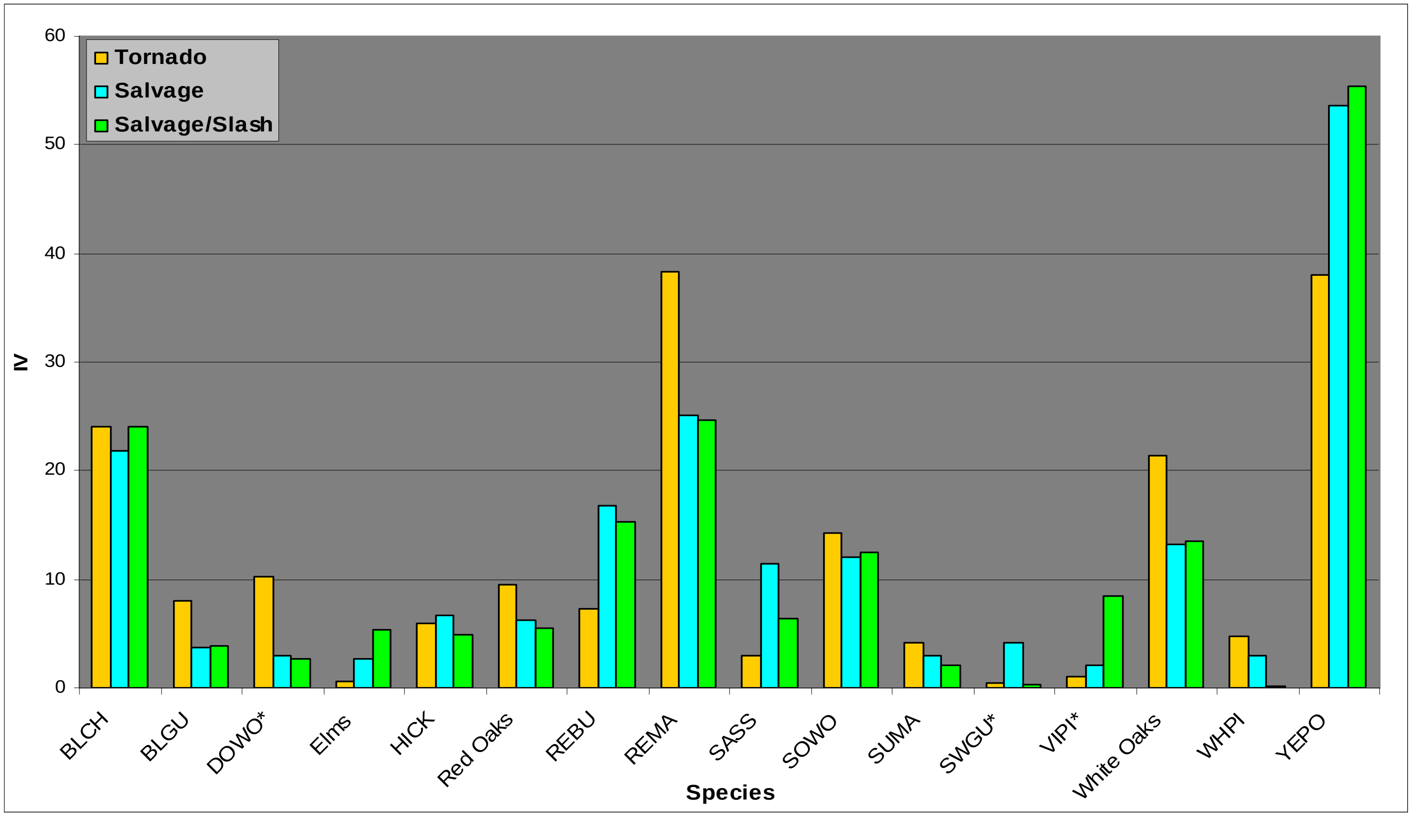


Figure 4.4: Importance values (out of 200) by species in the tornado disturbance treatments at the FRREC in Oak Ridge, TN. Tornado treatment is represented by orange, salvage by blue, and salvage/slash by green. See Appendix for species codes and names. (signifies statistically significant differences ($p \leq 0.05$) between treatments for a given species, $\alpha = 0.05$).*

Figure 4.5-A

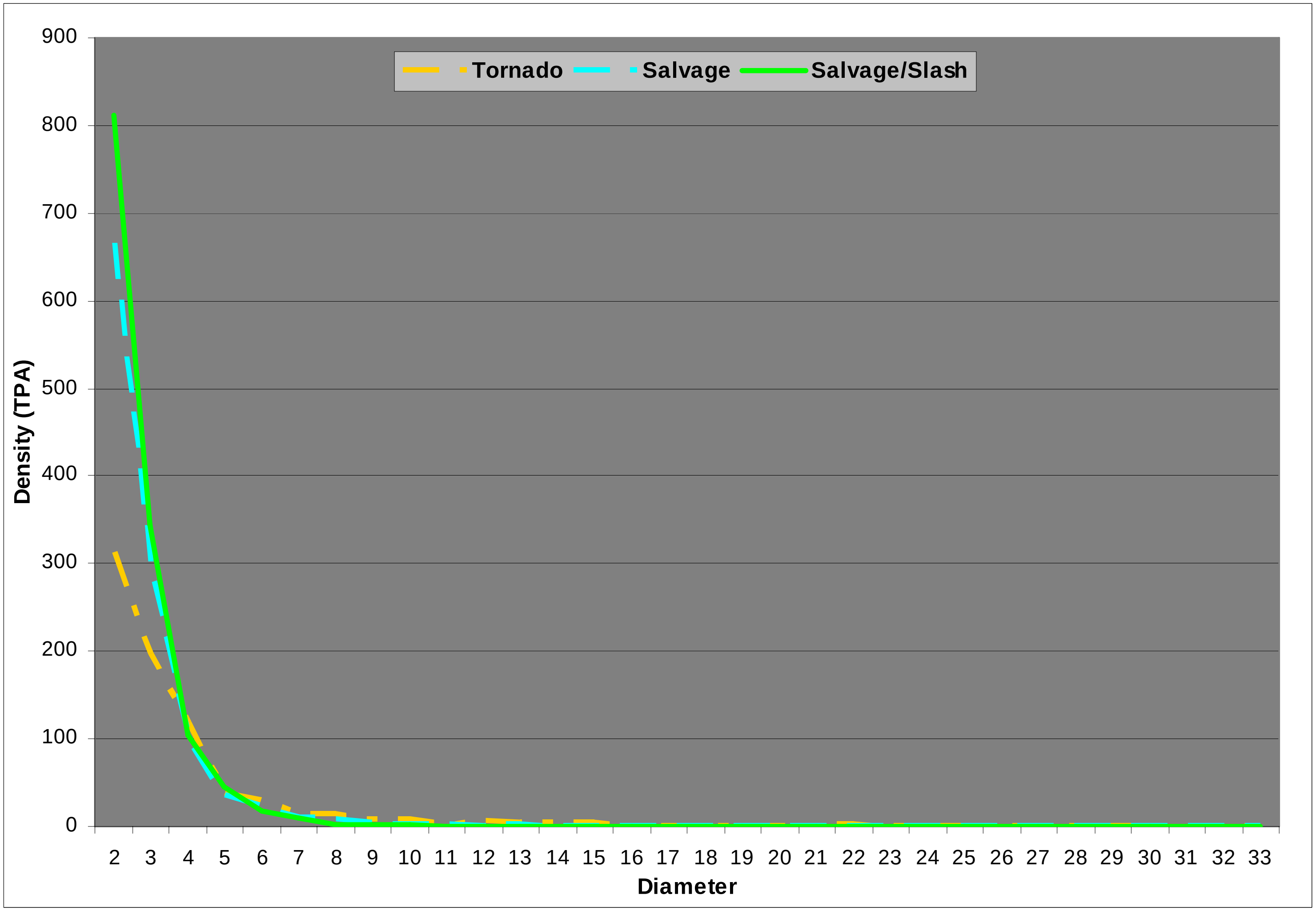
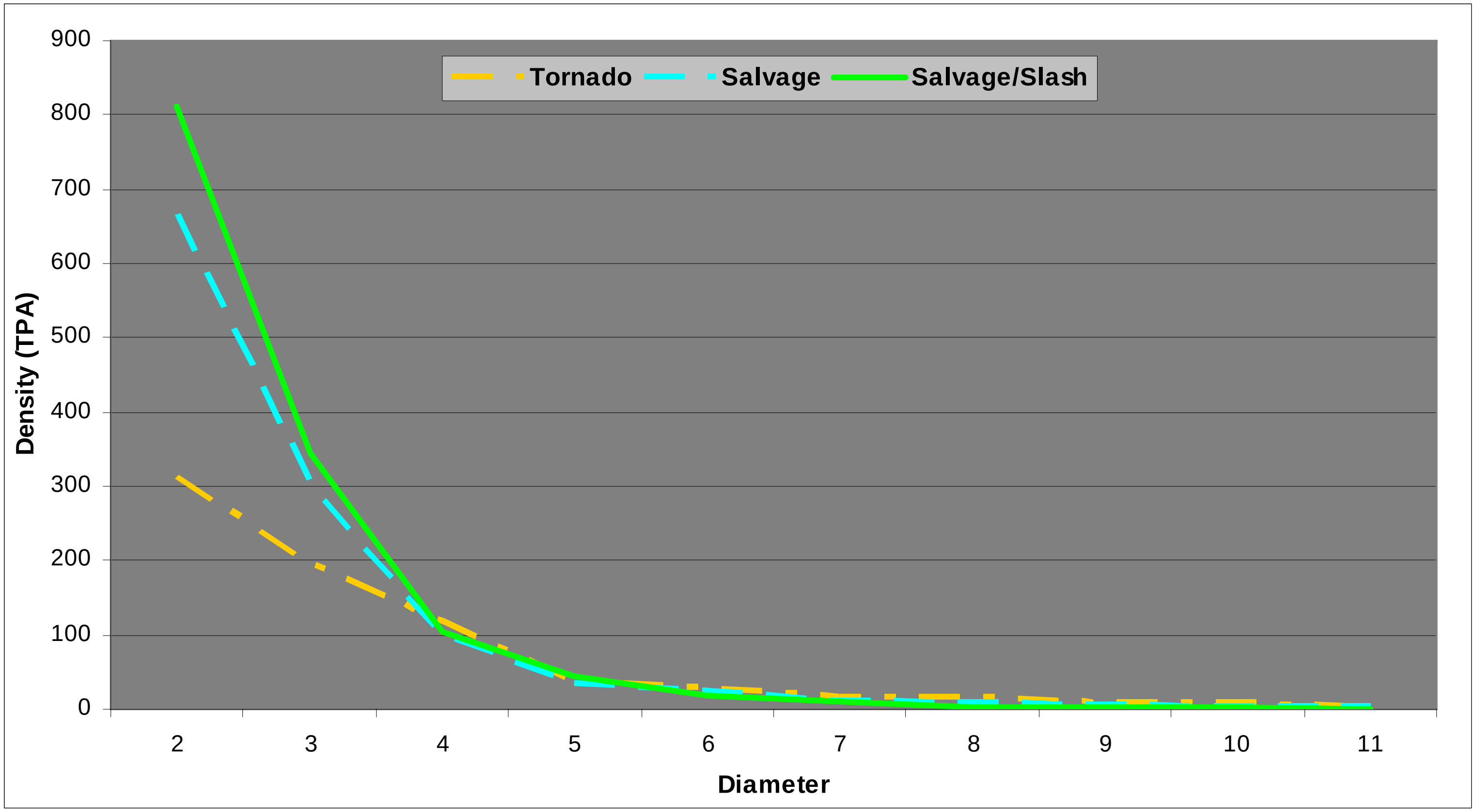


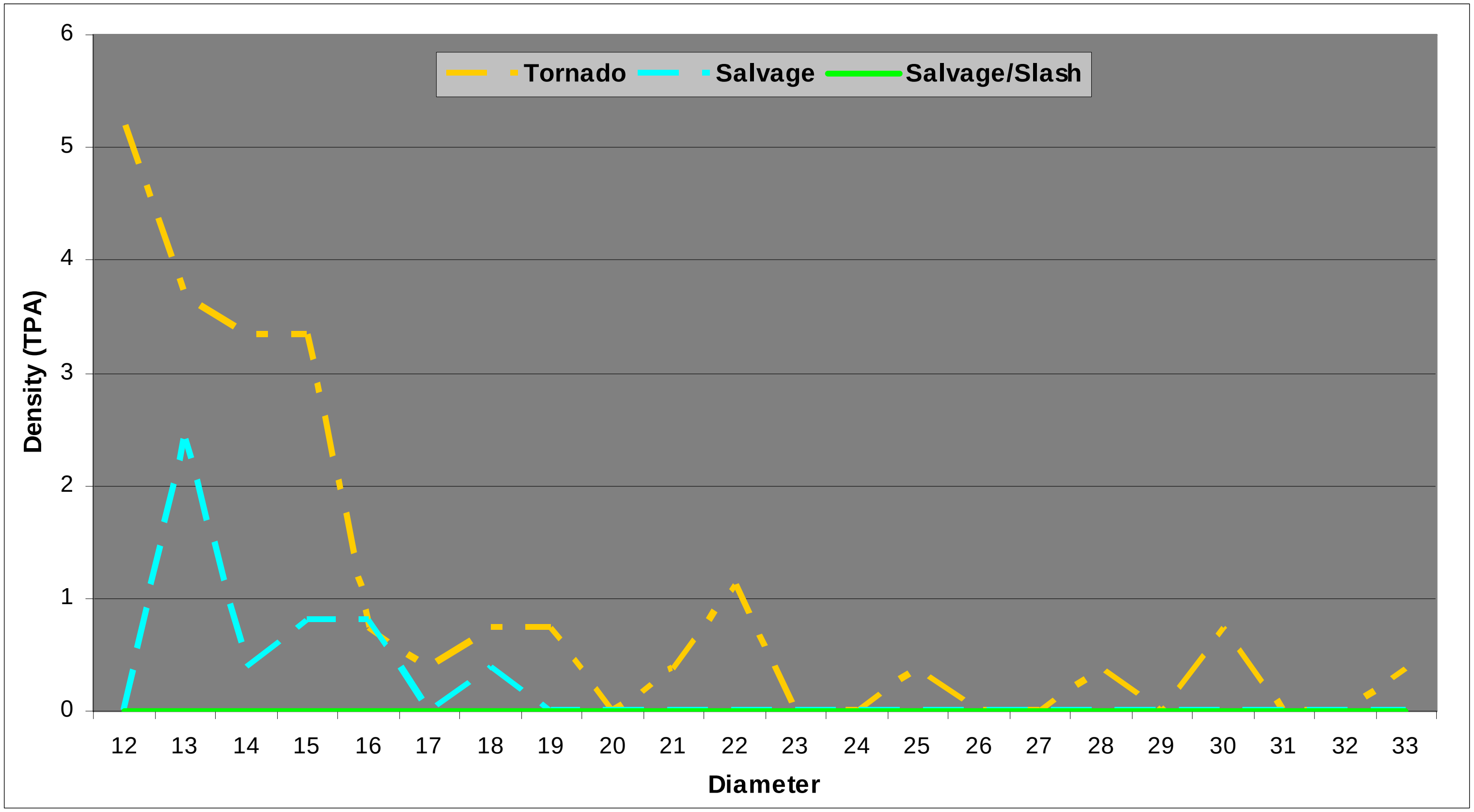
Figure 4.5, A-C: Tree density (trees per acre) for tornado, salvage, and salvage/slash treatments for entire range of diameters (A),trees ranging from 2" to 11"DBH (B), and trees ≥ 12" DBH (C) at the FRREC in Oak Ridge, TN.

Figure 4.5-B.



Tornado
Salvage
Salvage/Slash
900
800
700
600
500
400
300
200
100
0
Density (TPA)
2
3
4
5
6
7
8
9
10
11
Diameter

Figure 4.5-C.



Tornado
Salvage
Salvage/Slash
Density (TPA)
6
5
4
3
2
1
0
12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33
Diameter

Diameter distribution curves in salvage/slash areas (Figure 4.6-B) show similar relationships to the salvage treatment. Although the density for each species in the each diameter class is higher in the salvage/slash (at least in the 2- to 5-inch classes) the diameter distribution curves resemble those of the salvage treatment. The same five species were used from the IV calculations and the order (by species density) was also the same for both treatments (Table 4.4-B). The primary difference between the two treatments is that the salvage/slash areas had fewer trees in the larger diameter classes.

Diameter distribution curves indicate that the tornado treatment is the only treatment where yellow-poplar did not dominate the 2- to 4-inch classes (Figure 4.6-C). However, yellow-poplar has the highest overall density in the tornado area, and has the greatest density from the 5- to 18-inch diameter classes, as well as the 25-, 28-, and 30-inch classes (Table 4.4-C). Red maple was the dominant species in the 2- and 3-inch classes, but no red maple exists beyond the 13-inch class. No black cherry exists beyond the 11-inch class, and no sourwood exists beyond the 10-inch class. White oak, aside from having the lowest density of the five species, has a similar distribution as yellow-poplar from the 11- to 21-inch diameter classes with a lesser density.

Shannon Diversity

All strata analyzed for Shannon diversity showed significant treatment differences except when midstory and overstory strata were combined (Table 4.5). For understory > 4 ft. and midstory strata, the tornado treatment diversity was significantly less than both salvage and salvage/slash, but no differences existed between salvage and salvage/slash. Differences

Figure 4.6-A.

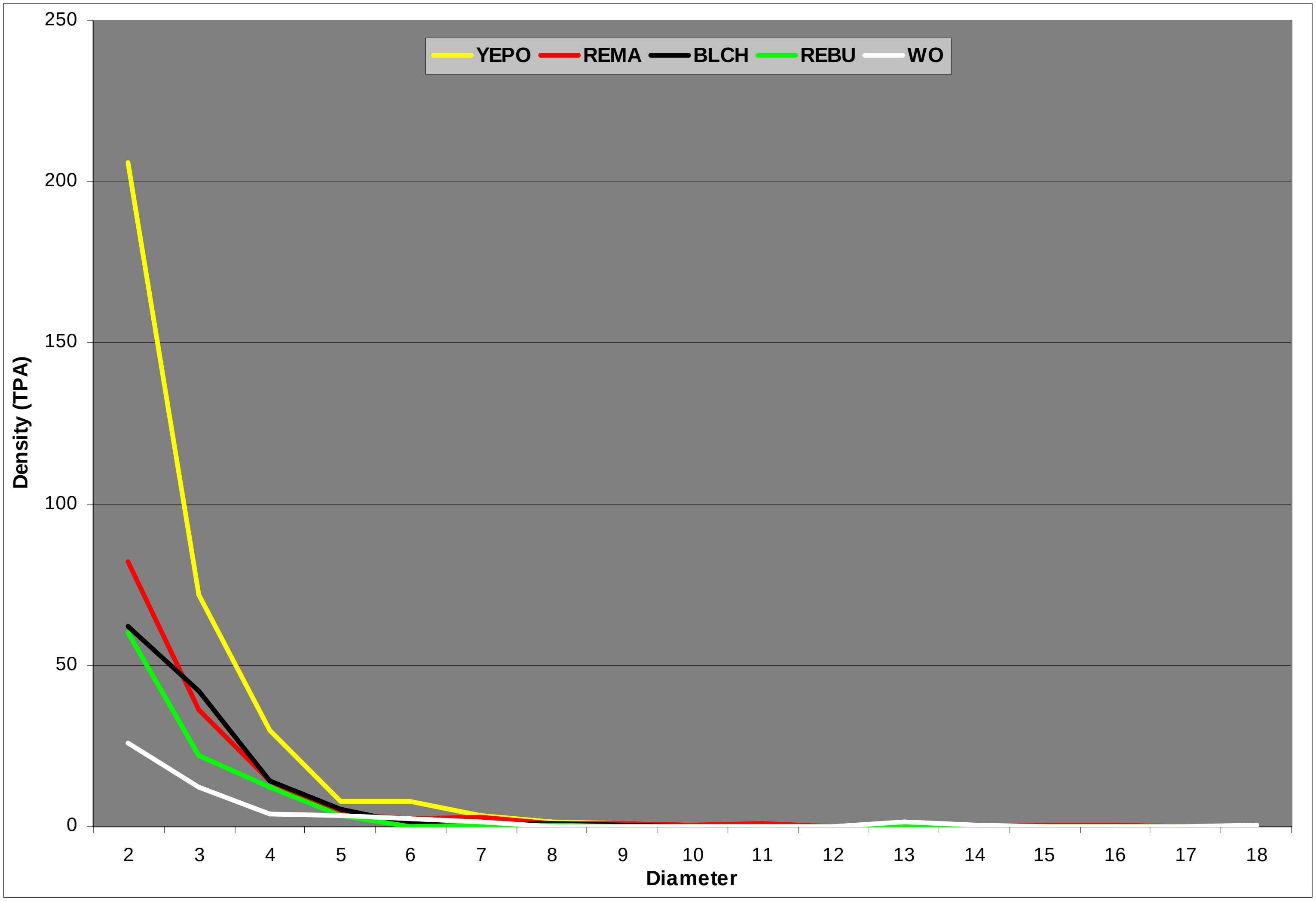
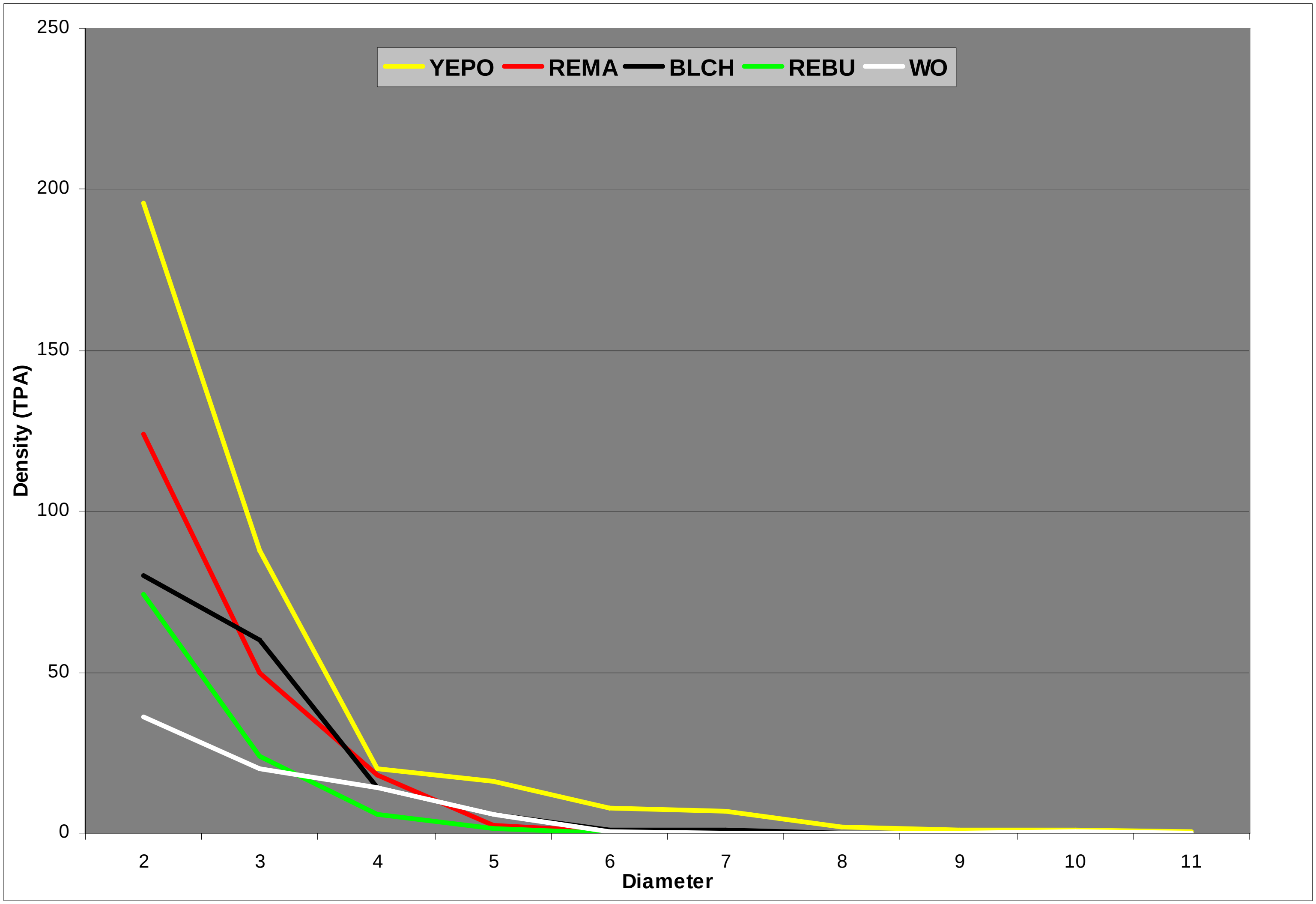


Figure 4.6, A-C: Diameter distribution curves for Salvage (A), Salvage/Slash (B), and Tornado (C) treatments based on density (trees per acre) and diameter at the FRREC in Oak Ridge, TN. Differing diameter ranges along the X-axis in each sub-figure (A-C) are based on the largest diameter tree found in the given treatment. Species reported vary for each treatment and are based on the species with the five greatest IV's for each treatment.

Figure 4.6-B.



250
200
150
100
50
0
Density (TPA)
YEPO
REMA
BLCH
REBU
WO
2
3
4
5
6
7
8
9
10
11
Diameter

Figure 4.6-C.

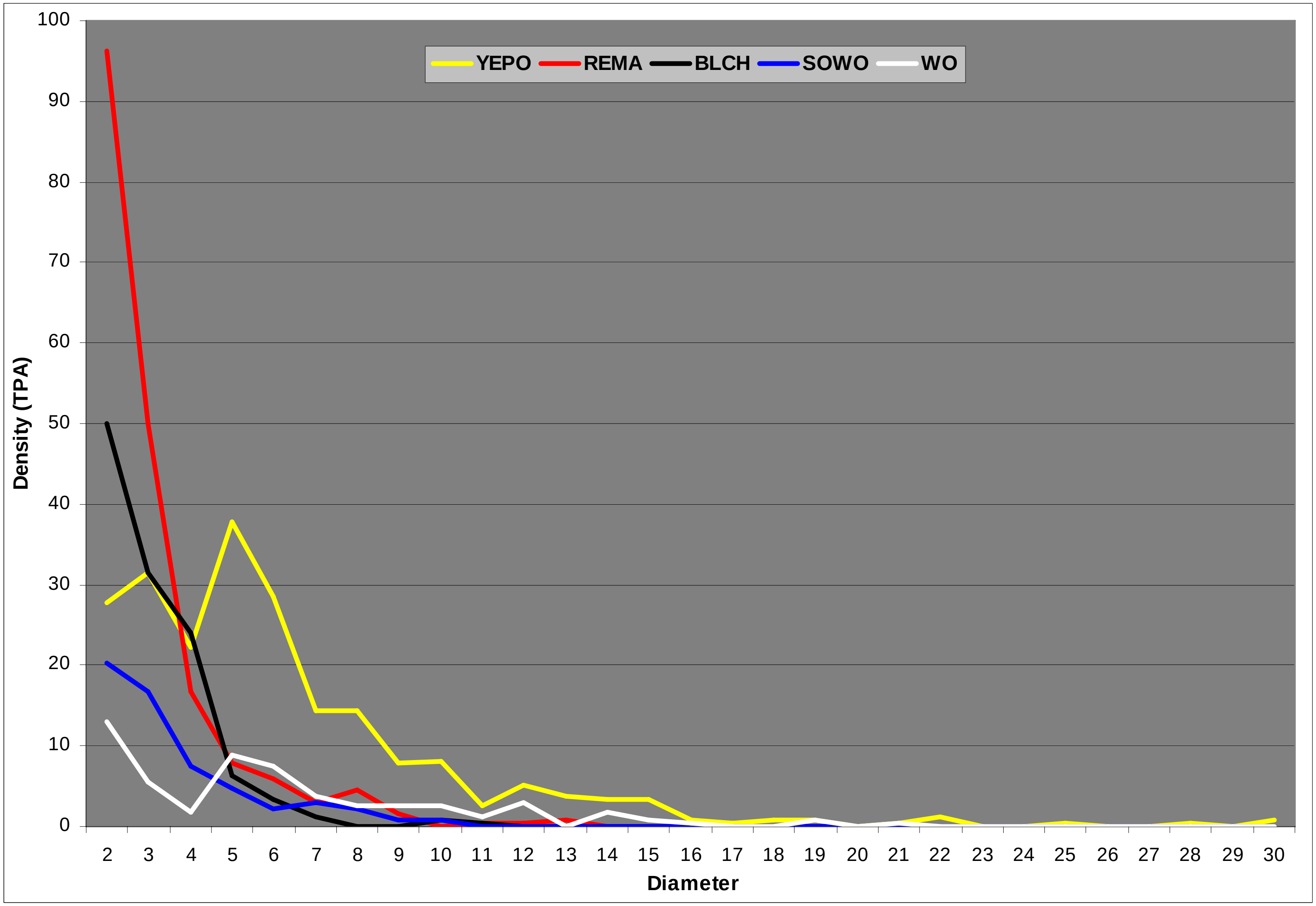

YEPO
REMA
BLCH
SOWO
WO
Density (TPA)
100
90
80
70
60
50
40
30
20
10
0
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
Diameter

Table 4.4 A-C: Tree densities (trees per acre) by diameter class for Salvage (A), Salvage/Slash (B), and Tornado (C) disturbances at the FRREC in Oak Ridge, TN. Species reported vary for each treatment and are based on the species with the five greatest IV's for each treatment. See Appendix for species codes and names.

A.

DBH	**YEPO**	**REMA**	**BLCH**	**REBU**	**WO**	**Total**
2	206	82	62	60	26	666
3	72	36	42	22	12	302
4	30	14	14	12	4	98
5	8	4	5.6	3.2	3.6	34.4
6	7.6	2.4	0.8	0	2.4	22.4
7	3.6	2.8	0.4	0.4	1.6	10.8
8	1.6	1.2	0.8	0.4	0	8.8
9	1.2	0.8	0.4	0	0	4.4
10	0.4	0.4	0	0	0	2.4
11	0.4	0.8	0	0	0	2
12	0	0	0	0	0	0
13	0.4	0	0	0	1.6	2.4
14	0	0	0	0	0.4	0.4
15	0	0.4	0	0	0	0.8
16	0.4	0.4	0	0	0	0.8
17	0	0	0	0	0	0
18	0	0	0	0	0.4	0.4
Total Density	331.6	145.2	126	98	52	1156
Relative Density	0.28685	0.12561	0.109	0.08478	0.04498	

B.

DBH	**YEPO**	**REMA**	**BLCH**	**REBU**	**WO**	**Total**
2	196	124	80	74	36	812
3	88	50	60	24	20	344
4	20	18	14	6	14	104
5	16	2.4	6	1.6	6	44.8
6	8	0.4	0.8	0	0.4	17.2
7	6.8	0	0.8	0	0	10
8	2	0	0	0	0	2.4
9	1.2	0	0	0	0	1.6
10	1.2	0	0	0	0.4	1.6
11	0.4	0	0	0	0	0.4
Total Density	339.6	194.8	161.6	105.6	76.8	1338
Relative Density	0.25381	0.14559	0.12078	0.07892	0.0574	

Table 4.4 A-C: con't.

C.

DBH	**YEPO**	**REMA**	**BLCH**	**SOWO**	**WO**	**Total**
2	28	96	50	20	13	313
3	31	50	31	17	6	196
4	22	17	24	7	2	119
5	38	8	6	4.8	9	38
6	29	6	3.3	2.2	7	29
7	14	3.0	1.1	3.0	3.7	14
8	14	4.4	0	2.2	2.6	14
9	8	1.5	0	0.7	2.6	8
10	8	0	0.7	0.7	2.6	8
11	3	0.4	0.4	0	1.1	3
12	5	0.4	0	0	3.0	5
13	3.7	0.7	0	0	0	4
14	3.3	0	0	0	1.9	3
15	3.3	0	0	0	0.7	3
16	0.7	0	0	0	0.4	1
17	0.4	0	0	0	0	0
18	0.7	0	0	0	0	1
19	0.7	0	0	0	0.7	1
20	0	0	0	0	0	0
21	0.4	0	0	0	0.4	0
22	1.1	0	0	0	0	1
23	0	0	0	0	0	0
24	0	0	0	0	0	0
25	0.4	0	0	0	0	0
26	0	0	0	0	0	0
27	0	0	0	0	0	0
28	0.4	0	0	0	0	0
29	0	0	0	0	0	0
30	0.7	0	0	0	0	1
Total Density	216.3	187.0	117.4	58.1	56.3	763
Relative Density	28.4%	24.5%	15.4%	7.6%	7.4%	

Table 4.5: Shannon H' values by treatment reported for each vegetation strata in the tornado disturbance treatments at the FRREC in Oak Ridge, TN. P-values are reported for the overall model (signifies p ≤ 0.05). Different letters signify statistically significant differences between treatments using least significant differences.*

vegetation strata	**Tornado Sa**		**lvage**		**Salvage/Slash**		p-value
Understory > 4 ft.*	0.663	B	1.181	A	1.050	A	0.0044
Midstory*	1.337	B	1.574	A	1.676	A	0.0057
Overstory*	1.505	A	1.348	B	1.019	C	<0.0001
Midstory/Overstory	1.785	A	1.821	A	1.818	A	0.915

existed between all treatments in the overstory strata where tornado areas had the highest diversity followed by salvage and salvage/slash, respectively.

Non-metric Multidimensional Scaling

All vegetation strata, except the understory woody vegetation > 4 ft., demonstrated significant treatment effects on plant community composition (Table 4.6). The treatment pairwise analysis shows that most community differences can be found between the tornado treatment compared to the salvage and salvage/slash treatments (Table 4.7). For all vegetation strata except understory woody vegetation > 4 ft., a treatment difference was detected between tornado and the two other treatments. However, salvage and salvage/slash treatments were not significantly different from each other except in the overstory vegetation (Table 4.7).

Several significant differences were found when the two areas within treatments were compared (Table 4.8). The two tornado areas were significantly different at the understory herbaceous and overstory strata levels. The two salvage areas were significantly different at all strata except the understory herbaceous level. Salvage and slash areas were only significantly different at the understory woody < 4 ft. level.

Table 4.6: Non-metric multidimensional scaling ANOSIM Global-R and p-values by vegetation strata for analysis for treatments and treatment areas in the tornado disturbance treatments at the FRREC in Oak Ridge, TN. (signifies $p \leq 0.05$).*

	Treatment		**Treatment Area**	
vegetation strata	*R*	p-value	*R*	p-value
Understory Herbaceous	0.03	0.004*	0.046	0.001*
Understory Woody<4	0.039	0.001*	0.135	0.001*
Understory Woody>4	0.01	0.104	0.039	0.002*
Midstory	0.101	0.001*	0.169	0.001*
Overstory	0.167	0.001*	0.182	0.001*

Table 4.7: Treatment pairwise tests between all possible treatment pairs for each vegetation strata in the tornado disturbance treatments at the FRREC in Oak Ridge, TN. (T = Tornado, S = Salvage, and SS= Salvage/Slash) (signifies $p \leq 0.05$)*

	Understory Herbaceous		**Understory Woody < 4'**		**Understory Woody > 4'**		**Midstory**		**Overstory**	
treatment pair	R	p-value	R	p-value	R	p-value	R	p-value	R	p-value
T, S	0.045	0.003*	0.051	0.003*	0.017	0.071	0.176	0.001*	0.098	0.003*
T, SS	0.031	0.016*	0.042	0.005*	0.014	0.087	0.131	0.001*	0.251	0.001*
S, SS	0.015	0.093	0.024	0.06	-0.002	0.557	-0.014	0.682	0.131	0.001*

Table 4.8: Treatment area pairwise tests for each vegetation strata in the tornado disturbance areas at the FRREC in Oak Ridge, TN. (T = Tornado, S = Salvage, and SS Salvage/Slash; numbers represent treatment area) (signifies $p \leq 0.05$)*

	Understory Herbaceous		**Understory Woody < 4'**		**Understory Woody > 4'**		**Midstory**		**Overstory**	
block pairs	R	p-value	R	p-value	R	p-value	R	p-value	R	p-value
T1, T2	0.060	0.013*	0.016	0.258	0.007	0.587	0.082	0.072	0.109	0.029*
S1, S2	0.032	0.101	0.349	0.001**	0.147	0.001**	0.214	0.004*	0.131	0.027*
SS1, SS2	0.013	0.209	0.169	0.001**	0.033	0.099	0.083	0.068	0.023	0.639

At the treatment and treatment area level, differences most often exist at the overstory strata and most seldom exist at the understory woody vegetation > 4 ft. The three remaining strata all showed the same differences between treatments. Treatment area comparisons show that the understory woody > 4 ft. strata provide the second highest number of community differences followed by the midstory, understory herbaceous, and understory woody vegetation > 4 ft., respectively.

Figure 4.7 A-E shows the overlap of treatment groups in the NMDS ordination. The herbaceous strata (Figure 4.7-A) had the second lowest correlation value which is indicated by the scattering of points all over the plot (i.e. high dissimilarity). Although the x-axis and y-axis are unit-less, a large percentage of points are located at 0,0 on the plot. The woody < 4 ft. (Figure 4.7-B) strata had relatively greater, but still low correlation. This is indicated by the overlap of all treatments across the plot, but with no centralized point as is the herbaceous strata. The woody > 4 ft. (Figure 4.7-C) had the lowest *R* value of all strata. Like the herbaceous strata, these plots had a high percentage of points at the 0,0 location of the x-axis and y-axis.

The midstory and overstory strata (Figure 4.7-D and E, respectively) showed the highest correlations between treatment and vegetation community of all five strata. In the midstory strata, all three treatments group relatively well compared to other strata, with the salvage treatment having the most dissimilar community. The overstory strata had the greatest correlation (R=0.182) with the tornado treatment having the most dissimilar community, relative to the salvage and slash/salvage treatments.

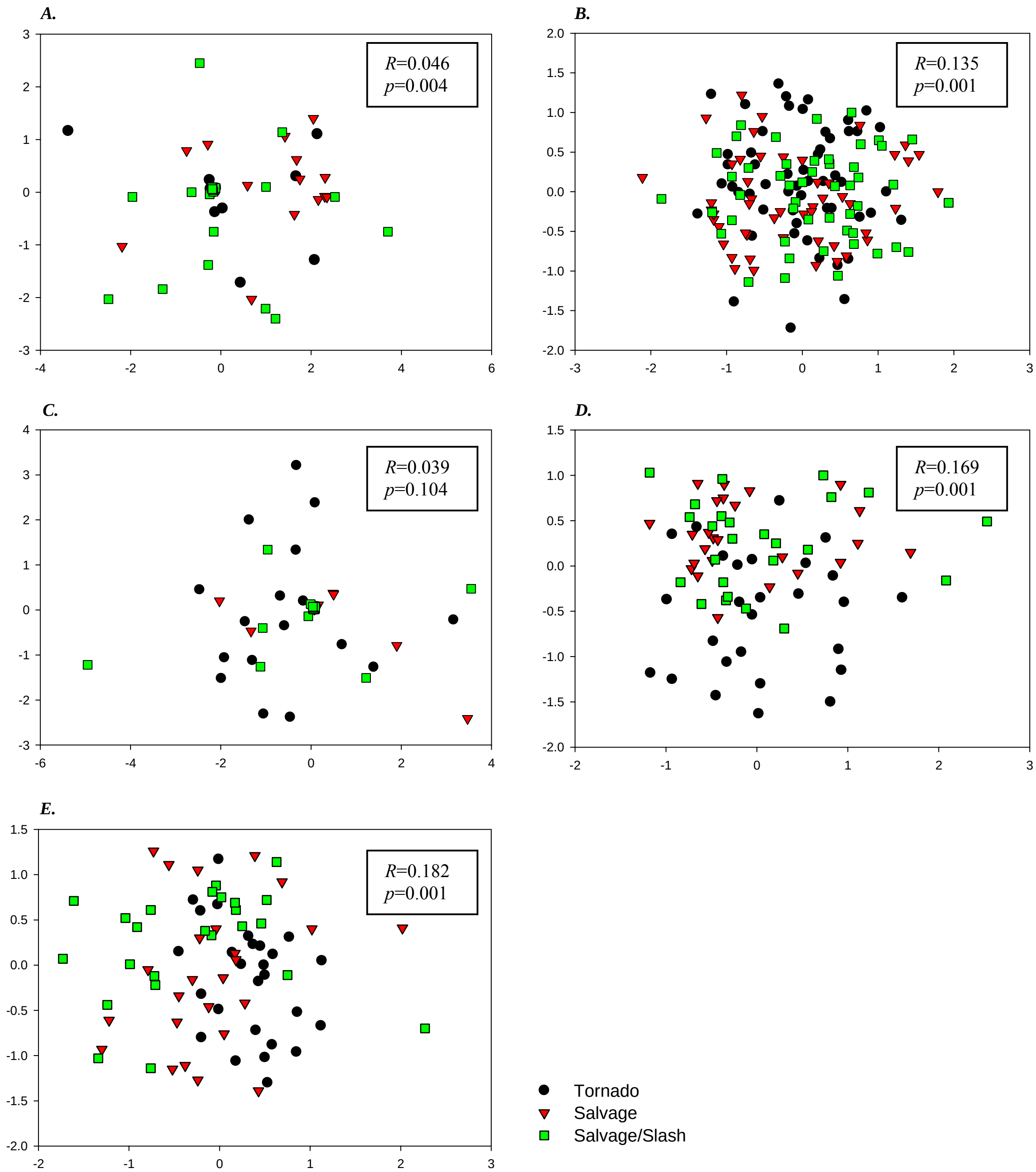


Figure 4.7 A-E: Non-metric multidimensional scaling X,Y scatter plot for five vegetation strata: Understory - herbaceous (A), Understory - woody vegetation < 4 ft. (B), Understory - woody vegetation > 4 ft. (C), Midstory (D), and Overstory (E) in the tornado disturbance treatments at the FRREC in Oak Ridge, TN. Scatter plots are separated by treatment and associated global R and p-values from the Analysis of Similarity (ANOSIM) are reported.

Coarse Woody Debris

Significant treatment differences were detected for CWD volume and CWD biomass (Table 4.9) which indicate the potential to influence wildlife. Although CWD density is related to both volume and biomass, no significant differences were detected between treatments. The tornado treatment had significantly greater CWD volume than both the salvage and salvage/slash treatments. CWD volume was roughly four times greater in the tornado areas compared to the salvage areas and roughly two times greater compared to the salvage/slash areas. The salvage/slash areas contained more than twice the CWD volume, but were not significantly different from the salvage areas. The tornado areas contained nearly three times and significantly higher amounts of CWD biomass than both treatments. The salvage/slash treatment contained over three times the amount of CWD biomass compared to the salvage areas and was significantly higher compared to the salvage areas.

Table 4.9: Coarse woody debris volume (ft^3/ac), density (logs/acre), and biomass (tons/ac) by treatment in the tornado disturbance treatments at the FRREC in Oak Ridge, TN. P-values are reported for the overall model (signifies $p \leq 0.05$). Different letters signify statistically significant differences between treatments using least significant differences*

CWD attribute	**Tornado Sa**		**lvage**		**Salvage/Slash**		p-value
Volume (ft3/ac)*	635.9	A	157.8	B	323.1	B	0.0005
Density (logs/ac)	108.1	A	114.1	A	98.0	A	0.6977
Biomass (tons/ac)*	0.666	A	0.073	C	0.231	B	<0.0001

DISCUSSION

Species Composition

Importance Values - Importance values analysis was the primary tool used to describe species composition because it scored each species based on its abundance and basal area relative to all other species. The null hypothesis can only be rejected for three of the sixteen species analyzed: dogwood, sweetgum and Virginia pine. No species showed treatment effects for all three treatments. Dogwood only showed a treatment difference for the tornado treatment, sweetgum only showed a difference for the salvage treatment, and Virginia pine only showed a difference for the salvage/slash treatment (Table 4.2).

The treatment differences for the above three species can be attributed to residual canopy coverage and the shade tolerance of individual species. The tornado treatment had the lowest level of disturbance, and therefore, the greatest canopy coverage from residual trees. This created a light regime that is the most conducive of all the treatments to shade tolerant species. This is a result of the residual overstory trees that were not blown down by the tornado, nor harvested in a salvage operation. Conversely, the salvage/slash treatment had the highest level of disturbance, affected by three different disturbances: the 1993 tornado, the subsequent salvage harvest, and the slashing that followed the salvage harvest. This area had no residual canopy coverage. It provided the most favorable conditions for shade intolerant species as no residual trees were left after disturbance, simulating silvicultural clearcut light conditions. Out of the three treatments examined, the salvage treatment resulted in an intermediate level of disturbance, reflected by its level of canopy cover and the favorable response of both tolerant and intolerant species.

Flowering dogwood, a shade tolerant species (Burns and Honkala 1990), had an IV over three times greater in the tornado area than the salvage and salvage/slash area. This may be explained by the residual overstory canopy and the shade it casts on the new cohort where flowering dogwood resided. Virginia pine, however, experienced the opposite treatment effect as it is a shade intolerant species (Burns and Honkala 1990). It had an IV over 4 times greater in the salvage/slash treatment compared to the other two treatments. These finding are similar to those in the literature that reported how disturbance intensity effected species composition (Peterson 2000). Disturbances of greater intensity, which removed a greater proportion of the canopy, will result in a more shade intolerant species composition in the new cohort, and visa versa (Runkle 1982, Runkle 1985, Clinton et al. 1994).

The three species with the greatest IV's were the same for each treatment: yellow-poplar, red maple and black cherry, although in different quantities in each treatment. All three of these species are generally considered early successional species, so their high importance was to be expected. White oaks consistently had the fifth highest IV for all treatments. They are considered to be a remnant component of the pre-disturbance stand. Sourwood (*Oxydendrum arboreum*) (salvage and salvage/slash) and redbud (tornado) had the fourth highest IV. This data suggested that regardless of post-tornado disturbance occurrence or its intensity, yellow-poplar, red maple, black cherry, and white oak will likely be part of the post-disturbance stand shortly after canopy closure (i.e. 14 years post-disturbance).

Non-metric multidimensional scaling - Results from the NMDS analysis demonstrated that significant changes in community composition occurred between treatments at all levels but the understory > 4 ft. stratum. Therefore, except for the aforementioned stratum, the null hypothesis can be rejected for all strata. The understory > 4 ft. stratum typically had the lowest tree density of all the strata in all treatments, which was possibly why no significant differences were detected. Some treatment area differences were detected within individual treatments, demonstrating that some level of variability existed within treatments. However, the variability was not great enough to mask the differences observed at treatment level.

Pairwise tests (Table 4.7) illustrated that the tornado treatment was equally dissimilar to both the salvage and salvage/slash treatments, and that salvage and salvage/slash treatments are more similar to each other than either is to the tornado. Furthermore, salvage and salvage/slash treatments only differed in the overstory stratum. This was to be expected, because the salvage treatment had a number of residual trees left in the overstory. The majority of the residual trees were shade tolerant species such as sourwood, black gum, and red maple (Burns and Honkala 1990). Trees in the overstory in the salvage/slash treatment were shade-intolerant to intermediate species such as yellow-poplar, black cherry, and white oak species (Burns and Honkala 1990). These results demonstrate that the additional slashing disturbance had no effect on the overall community composition of the salvaged areas, except in the overstory.

Tree Density and Structure

Although no statistical analysis was conducted to test for treatment differences in diameter distribution, differentiation appears to exist, especially in the larger diameter classes. As expected, salvage/slash areas had the greatest density of small diameter (2- to 5-inch) trees as the larger trees were salvaged. Salvage areas had similar distribution in these diameter classes, with slightly fewer trees. Both of these treatments had a steep negative exponential curve, whereas the tornado treatment had a less extreme negative exponential curve.

The structural diversity of the tornado treatment was more apparent than the other two treatments (Figures 4.5-A and C). It is in the complex stage of stand development and thus its distribution curve does not level out with increasing diameter like the others until the maximum diameter is reached. Larger diameter trees, although not evenly spaced, gave the tornado treatment an appearance of a stand managed for a two-age stand structure. Large diameter trees, mostly oaks, exist far above the new cohort. The shade cast by these older, larger trees result in lower stem densities below.

The high density of red maple in the 2- and 3-inch classes (Figure 4.6-C) is largely from stump sprouts. They are not expected to play a large role in the future of this stand, regardless of their dominance in these lower diameter classes. Field observations suggest that many of the stumps sprouts have died (not reported) and many more are showing signs of future density-related mortality associated to intraspecific competition (Burns and Honkala 1990).

Yellow-poplar and white oak have the highest densities in the 10-inch class and above. These trees are from both the residual stand and the new cohort, and will presumably make a considerable proportion of this stand at maturity. In addition, residual red oaks (not seen in Figure 4.6-C as one of the five species with the highest IV's) will presumably comprise an additional proportion of the stand composition at maturity. They currently have canopy dominance because they are large diameter, residual trees most likely in the 100-120 year old age class. If the residual red oaks do not expire before the new cohort reaches their canopy height, they will maintain dominant crown position.

In the salvage treatment, red maple did not exist in as high a density in the 2- and 3-inch classes as it did in the tornado area. However, red maple still had the second greatest density only to yellow-poplar. Of the top five species in importance values (Table 4.3-A), white oak, red maple, and yellow-poplar were the only species with residual trees following the salvage harvest. Red oaks, white oaks, red maples, sourwoods, and black gums were trees left unharvested because of wind damage or poor stem quality. Many of the damaged midstory red maples, black gums and sourwoods resprouted from the main stem and experienced crown expansion because of the open canopy created by the tornado and salvage disturbances. Both sprouting and crown expansion caused canopy space above the new cohort to be occupied resulting in more shade than the salvage/slash areas.

Because of the slashing in the salvage/slash treatment, no trees greater than 11 inches (27.9 cm) remained. All trees in this treatment were of the 1994 cohort because of the complete stan-initiating disturbance. The canopy and diameter stratification that has occurred since harvest is a result of species competition differences (Oliver 1980, Oliver and Larson 1996). Species that are able to tolerate greater amounts of shade such as red maple and sourwood persist in the smaller diameter classes (2- to 5-inch class), but will likely not reach dominant or codominant canopy classes in the future. Yellow-poplar is abundant in the 2- to 6-inch classes, but has similar density as white oak in the larger diameter classes. Therefore, if diameter is an indication of future species success, white oak may play a similar role in the future of this stand as yellow-poplar, regardless of lower densities in smaller diameter classes. Such a trend would be comparable to Oliver (1978) where northern red oak persisted with and became dominant to black birch and red maple, but would contrast O'Hara (1986) where yellow-poplar retained greater densities than white oak.

Species Diversity

Treatment differences existed in all four strata analyzed with the Shannon Index (H') except the combined midstory/overstory strata. Thus, the null hypothesis can be rejected for understory > 4 ft., midstory, and overstory strata. The overstory was the only stratum that had a significant treatment difference for all three treatments. The other two strata indicated that differences existed between the tornado and the other two treatments.

The lower H' value for the tornado areas in the understory and midstory can be explained by the intensity of disturbance, residual canopy retention and the amount of light reaching the new cohort. As previously discussed, the residual overstory left standing consisted of large trees that had dominant to intermediate crown positions, resulting in a more structurally diverse stand casting more shade to the forest floor at the time of the new cohort's establishment. The vertical structure complexity led to less light reaching the forest floor and resulting in a lower H'. In contrast, both salvage and salvage/slash treatments had fewer or no residual trees in diameter classes 12 inches (30.5 cm) and greater. Hence, light levels in these treatments were likely higher at the time of the new cohort's establishment compared to the tornado treatment. Similar results have shown the less intense disturbance result in lower species diversity (Runkle 1982, Clinton et al. 1994, Peterson 2000).

Overstory H' was significantly affected by treatment for all three treatments and can be related to the level of treatment disturbance. The tornado had the lowest level of disturbance of all three treatments, resulting in the highest number of trees in the overstory stratum. Conversely, the salvage/slash treatment, with the highest level of disturbance, had the lowest number of trees in the overstory stratum resulting in a lower H'.

The midstory and overstory were combined into one stratum in this analysis because the assumption was that the trees that will comprise these stands at maturity existed in these two strata. Because of the complexity of mixed-species stand dynamics, it would be difficult to determine which trees will persist through the stem exclusion stage without data from multiple growing seasons. However, most trees less than 2 inches (5.1 cm) in diameter (trees in the understory strata) are unlikely to survive stem exclusion and become overstory trees.

Tornado areas had the lowest H' in the midstory strata but had the greatest H' in the overstory strata. Conversely, salvage and salvage/slash treatments had equally high H' in the midstory strata, but the middle and lowest H' scores for the overstory strata (respectively). This inverse relationship led to a balance in overall diversity, resulting in uniform species evenness (H') across all three treatments for the combined midstory/overstory strata.

Coarse Woody Debris

The tornado treatment had the largest amounts of CWD volume and biomass, followed by the salvage/slash, and lastly the salvage treatment. Therefore the null hypotheses for both of these attributes can be rejected. However, the null hypothesis for the CWD density attribute cannot be rejected due to a lack of any significant treatment difference.

The tornado area was expected to have the greatest CWD volume and biomass because no woody material was ever removed from these sites after the tornado disturbance. Greenberg (2001) similarly found that unsalvaged canopy gaps have greater percentage of

CWD compared to salvaged canopy gaps. Both the salvage and salvage/slash treatments had the same salvage harvest, but the addition of slashing resulted in greater CWD volume and biomass in the salvage/slash areas. Over the past fourteen years, small trees cut during the salvage/slash operation, and then left onsite, have decayed. However, larger trees that were felled and left have not decayed, and these trees contributed to significantly more CWD volume and biomass. The only remaining CWD on the salvage stands were logs that the salvage logging crew found unmerchantable and left behind. Many of these trees were unmerchantable species, were of poor form or were snapped in the middle bole, making recovery of a sawlog difficult (Richard Evans[†], personal communication).

Since the same hardwood decay reduction factors were used for all species in all treatments, CWD volume and biomass are related. Based on the equations used to calculate CWD volume and biomass, the bulk density and decay reduction factor coefficients are the variables that relate these to characteristics. However, the data indicated that CWD volume and biomass are not necessarily related to CWD density since all there was no significant differences detected between treatments. The salvage treatment had the greatest CWD density of all treatments, yet had lowest amounts of volume and biomass. This demonstrates that although CWD density in the salvage area is equal to other treatments, the small diameters and highly decayed pieces do not amount to a substantial amount of volume or biomass.

Management Implications

Vegetation - Among desired hardwood timber species, (i.e. yellow-poplar, red oak, white oak, hickory, and to some extent red maple) no treatment differences were detected.

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These five desired species compose close to half of the overall IV for each treatment. Therefore, it could be argued that regardless of whether post-tornado salvage disturbance takes place, the importance of desirable species will not differ between stands. Furthermore, the three species that showed significant treatment effects (flowering dogwood, Virginia pine, and sweetgum) make up only 4.5% of the average overall IV score for all treatments, and are not typically considered desirable timber species.

Because the tornado and salvage disturbances were incomplete stand scale disturbances, the addition of a new cohort adds complexity to these areas. The pre-tornado disturbance stand was two-aged, consisting of a 60-80 year old cohort and a 100-120 year old cohort. Therefore, it is possible that a complex, uneven-aged stand was created in the tornado treatment. With each of the two older cohorts seemingly existent within the tornado stand, the addition of a new cohort has created a three-aged, or uneven aged stand. Similarly, the salvage areas had at least one cohort (possibly two) remaining within the treatment, creating no less than a two-aged stand.

When residual, post-disturbance trees are left in a stand, such as in the tornado and salvage treatments, species composition is directly and indirectly affected. The shade cast by residual overstory trees will lead to a more shade-tolerant species composition in the new cohort (Miller et al. 2006). Therefore, if shade-intolerant to intermediate species, such as yellow-poplar and oak species are considered desirable, a complete stand initiating disturbance, such as the salvage/slash treatment will likely result in a greater density of these species.

Coarse Woody Debris - The results from this work suggested that unsalvaged, post-tornado stands provided much more CWD volume and biomass. Furthermore, larger CWD pieces found in the tornado areas were expected to last longer compared to the other treatments, as CWD decay is a function of piece size (Stevens 1997). This is important for long-term nutrient cycling (Mattson et al. 1987, Hunter 1990). Research of smaller canopy gaps in the Southern Appalachians suggested that salvage of post-wind disturbed stands had little effect on species richness or diversity breeding birds (Greenberg and Lanham 2001), reptiles and amphibians (Greenberg 2001), shrews (Greenberg and Miller 2004), and abundance/biomass of macroarthropods (Greenberg and Forrest 2003). These findings are regardless of the differences in percent CWD coverage between intact canopy gaps and salvaged canopy gaps in all the above studies.

Research Implications

High levels of variability exist in the tornado stands. The complexity of the horizontal structure of residual stand within the tornado area was created by the tornado itself affecting the vertical and horizontal structure of the new cohort (Miller et al. 2006). Variability was reduced with each subsequent disturbance (salvage and slashing) as more residual trees were removed from each treatment. This variability may explain why there were not many significant differences found in tree level importance values. This variability was apparent as some compositional differences exist within treatments (Table 4.7). However, the overriding consideration was that differences between treatments still exist, regardless of within-treatment variability.

The vegetation and CWD data collected in this study were only representative of one point along the successional gradient. The vegetation variability mentioned above was likely greater in years immediately following disturbance compared to the data reported in this study. Furthermore, variability was expected to decrease as the progression of the stand moved into the later stages of stem exclusion and into the understory reinitiation stages. Density-dependent mortality and site specific conditions should begin to eliminate some-off site pioneer species, such as yellow-poplar, that opportunistically invaded at the time of disturbance. The elimination of these species and decrease in overall stand densities should lead to a less variable system overall.

Coarse woody debris had a temporal aspect to it as well. Shortly after all three disturbances (tornado, salvage, and slashing), CWD loads were higher because wood decay had just begun. Therefore, as time progressed, losses in CWD loads in all three treatments were evident. Because decay is a function of size (Stevens 1997), I expected greater CWD biomass and volume in the tornado treatment for a longer period of time.

The research conducted in this study only reported on vegetation and CWD stand characteristics at one point along the succession gradient. Further research should be conducted at different stages of stand development of each of these treatments. Such research will indicate whether assumptions made in this study regarding future CWD loads and decay, future stocking and species composition were correctly presumed. Specifically, the long term fate of residual trees in the tornado area is of interest. Most of the residual oaks are from the 100-120 year old age-class. If the older residual trees were subject to wind-throw or age dependent mortality, a new aspect of complexity would be added to the tornado areas.

CHAPTER 5: Assessing Anthropogenic and Natural Disturbances: Vegetation Response to Similarly Aged Clearcut and Tornado Disturbances

METHODS

Vegetation and Coarse Woody Debris

In July of 2008, vegetation data in the two clearcut treatment areas were collected. The clearcut was harvested in 1989 as part of a site preparation study. The research compared four site preparation techniques: brown-and-burn, fell-and-burn, commercial clearcut and silvicultural clearcut. Each of twenty, one-acre (0.04-ha) treatment blocks were then planted half with white pine and half with loblolly pine on a 20-foot by 20-foot (6.1-m by 6.1-m) spacing. All trees measuring 6 feet (1.83 m) or taller were felled by hand shortly after the initial timber harvest took place (Andrews 1995). Since the time of this study, little to no white pine and few loblolly pines have survived in the silvicultural clearcut (SCC) blocks. Furthermore, the mortality of the planted white and loblolly pine was early enough in stand development to have a minimal effect on stand composition (Richard Evans[†], personal communication). For this reason, the SCC blocks were selected to compare natural disturbance to anthropogenic disturbance. The anthropogenic disturbance occurred four years prior to the tornado disturbance.

Vegetation and CWD measurements were conducted in the five one-acre SCC treatment blocks in similar fashion to the three tornado-disturbed treatments (see Chapter 4 Methods). However, due to area constraint (1-acre blocks), transects were not used to lay out

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plots as in the tornado, salvage, and salvage/slash treatments (transects were, however, still used as the data collection technique for CWD measurements). Instead, two vegetation plots were measured at each of the five one-acre SCC blocks. The two plots were positioned 40 feet (12.2 m) north and south of the SCC block center stake. If a planted pine was inside the plot or was determined to have an effect to the natural development of the vegetation within the plot, the plot was systematically moved 54 feet (16.5 m) parallel to the block boundary to the side of the block planted with white pine. Since planted white pine survival was so low in SCC, no plots were adversely affected. Shannon diversity (H'), importance values, and CWD volume, density, and biomass were all calculated. NMDS analysis and Mann-Whitney mean ranks were all computed in the same manner as the Tornado/Salvage/Salvage and Slash comparisons (see Chapter 4-Methods).

RESULTS

Variability

Total basal area and the associated errors were similar between the two treatments, having high variability (Table 5.1). Overstory basal area was much greater in the tornado treatment, but had a standard error that was 2.5 times greater than the clearcut treatment, illustrating the high variability in the tornado treatment.

Table 5.1: Overstory and total basal area calculations for Tornado (T) and Clearcut (CC) treatments at the FRREC in Oak Ridge, TN.

	T	**CC**
Overstory		
Mean Basal Area (ft^2/acre)	63.30	25.91
Standard Error	7.20	2.85
Total		
Mean Basal Area (ft^2/acre)	90.11	82.99
Standard Error	6.05	5.69

Importance Values

Thirteen species/species groups had an importance value greater than 4.0 in either the tornado or clearcut areas. Of those thirteen species only three species showed significant differences (α = 0.05) between tornado and clearcut treatments: black gum, redbud, and sugar maple (*Acer saccharum*) (Table 5.2). Yellow-poplar, red maple, black cherry, sourwood, and the white oak group have the five highest importance value for both tornado and clearcut treatments. However, red maple has the highest IV for tornado and yellow-poplar has the highest IV for clearcut treatments. Although large differences occur between importance values between species such as red oaks, smooth sumac (*Rhus glabra*), white pine, and yellow-poplar (Figure 5.1), there are no significant differences between the two treatments for those species.

Table 5.2: Importance values by species based on a maximum 200 possible value in the tornado disturbance treatments at the FRREC in Oak Ridge, TN. P-values are reported (signifies p ≤ 0.05). See Appendix for species codes and names.*

species	**Tornado**	**Clearcut**	p-value
BLCH	24.07	28.36	0.4392
BLGU*	8.25	1.4	0.0073
DOWO	10.39	5.85	0.0883
HICK	5.81	4.87	0.8083
REBU*	7.6	0	0.0072
Red Oaks	9.36	3.83	0.7089
REMA	38.13	42.05	0.8934
SMSU	0.39	4.13	0.2592
SOWO	14.46	23.89	0.0541
SUMA*	4.69	0.39	0.0411
White Oaks	21.58	19.83	0.7248
WHPI	4.7	0	0.0796
YEPO	36.65	55.35	0.2504

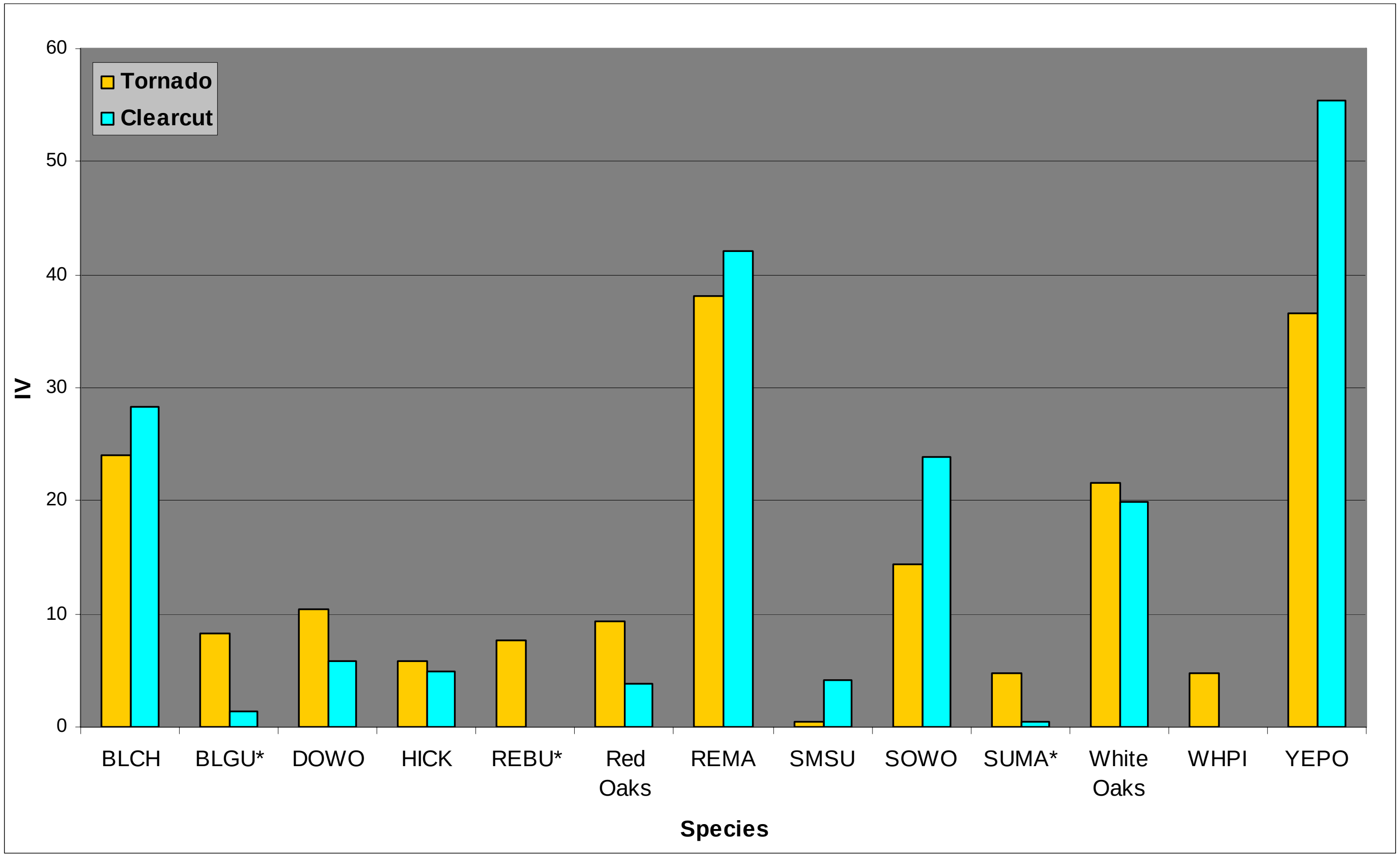


Figure 5.1: Importance values (out of 200) by species in the tornado disturbance treatments at the FRREC in Oak Ridge, TN. Tornado treatment is represented by orange and clearcut treatment is represented by blue. See Appendix for species codes and names. (signifies statistically significant differences between treatments for a given species, α = 0.05).*

Tree Density and Structure

Tree density curves for tornado and clearcut treatments had similar shape (Figure 5.2-A) but different densities, especially in the larger diameter classes. In the 2- to 7-inch diameter classes, the clearcut treatment averaged a higher stem density. However, all diameter classes greater than 7 inches (where trees were present) had greater stem densities in the tornado treatment (Figures 5.2-B and C). No trees in the 10-inch class or greater were found in the clearcut treatment.

Diameter distribution curves indicated that red maple is a dominant species in the 2-inch class for both tornado and clearcut treatments (Figure 5.3-A and B, respectively). This pattern continues in the tornado treatment for red maple into the 3-inch class as well. Yellow-poplar, which has the highest overall density in the tornado area, has the greatest density from the 5- to 18-inch diameter classes, as well as the 25-, 28-, and 30-inch classes (Table 5.3-A). No trees exist for red maple beyond the 13-inch class, for black cherry beyond the 11-inch class, and sourwood beyond the 10-inch class. White oak, however, has a similar distribution shape as yellow-poplar from the 11- to 30-inch diameter classes with a lesser density.

In the clearcut, red maple density quickly dropped and yellow-poplar had the greatest density in all other diameter classes (Figure 5.3-B). Sourwood was competitive in the 2- and 3-inch classes, but no trees existed beyond the 5-inch class. Black cherry had its highest density in the 4-inch class and had a slightly lesser density, but a similar distribution curve, as yellow-poplar in the 4- to 9-inch classes. White oak had the lowest overall density of the five selected species, but had the greatest density in the 7- to 9-inch classes (Table 5.3-B)

Figure 5.2-A.

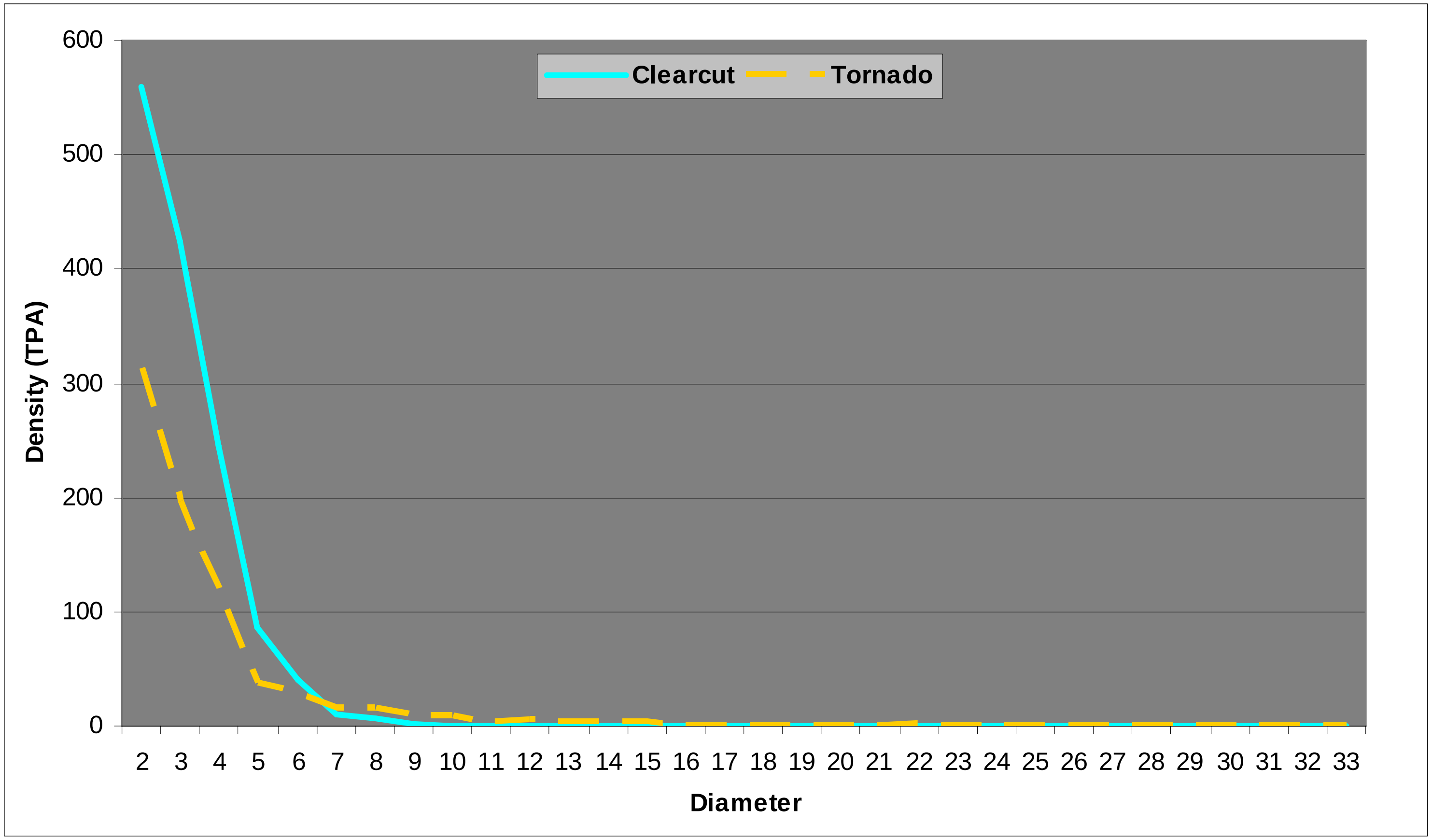
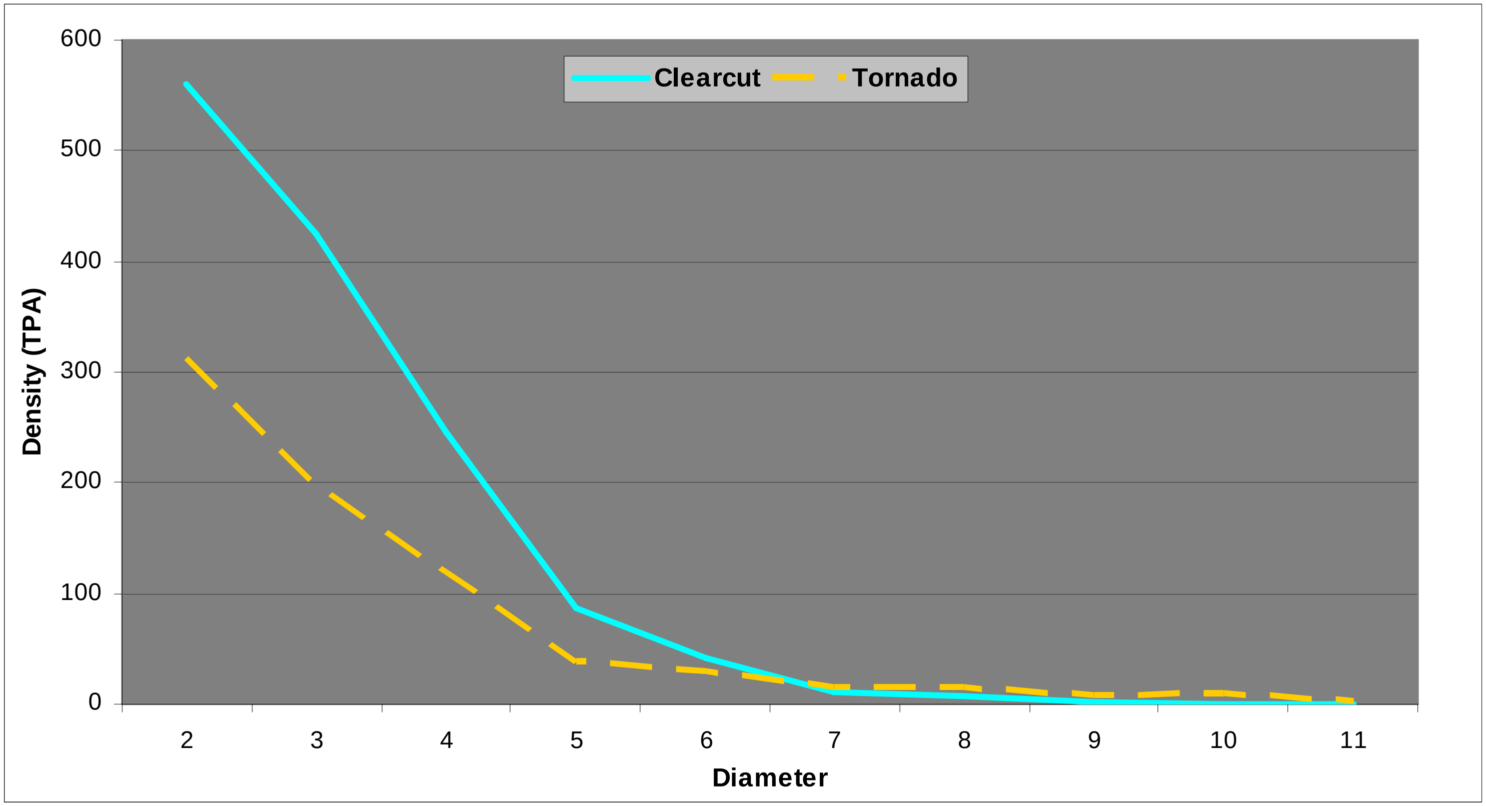


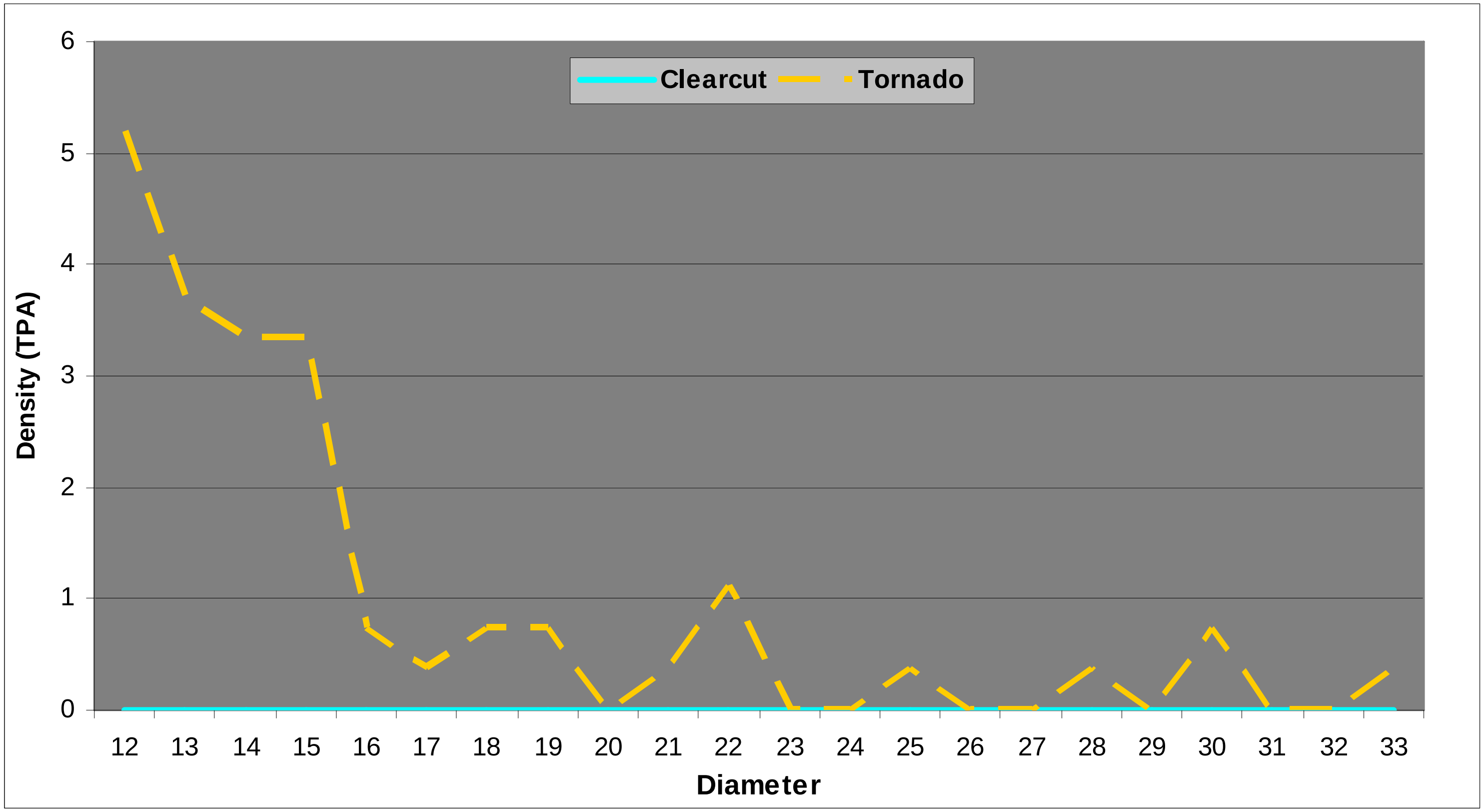
Figure 5.2 A-C: Tree density (trees per acre) for tornado and clearcut treatments for entire range of diameters (A), 2" to 11" trees (B), and trees ≥ 12" (C) at the FRREC in Oak Ridge, TN.

Figure 5.2-B.



600
500
400
300
200
100
0
Density (TPA)
Clearcut
Tornado
2
3
4
5
6
7
8
9
10
11
Diameter

Figure 5.2-C.



Clearcut
Tornado
Density (TPA)
0
1
2
3
4
5
6
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
Diameter

Figure 5.3-A.

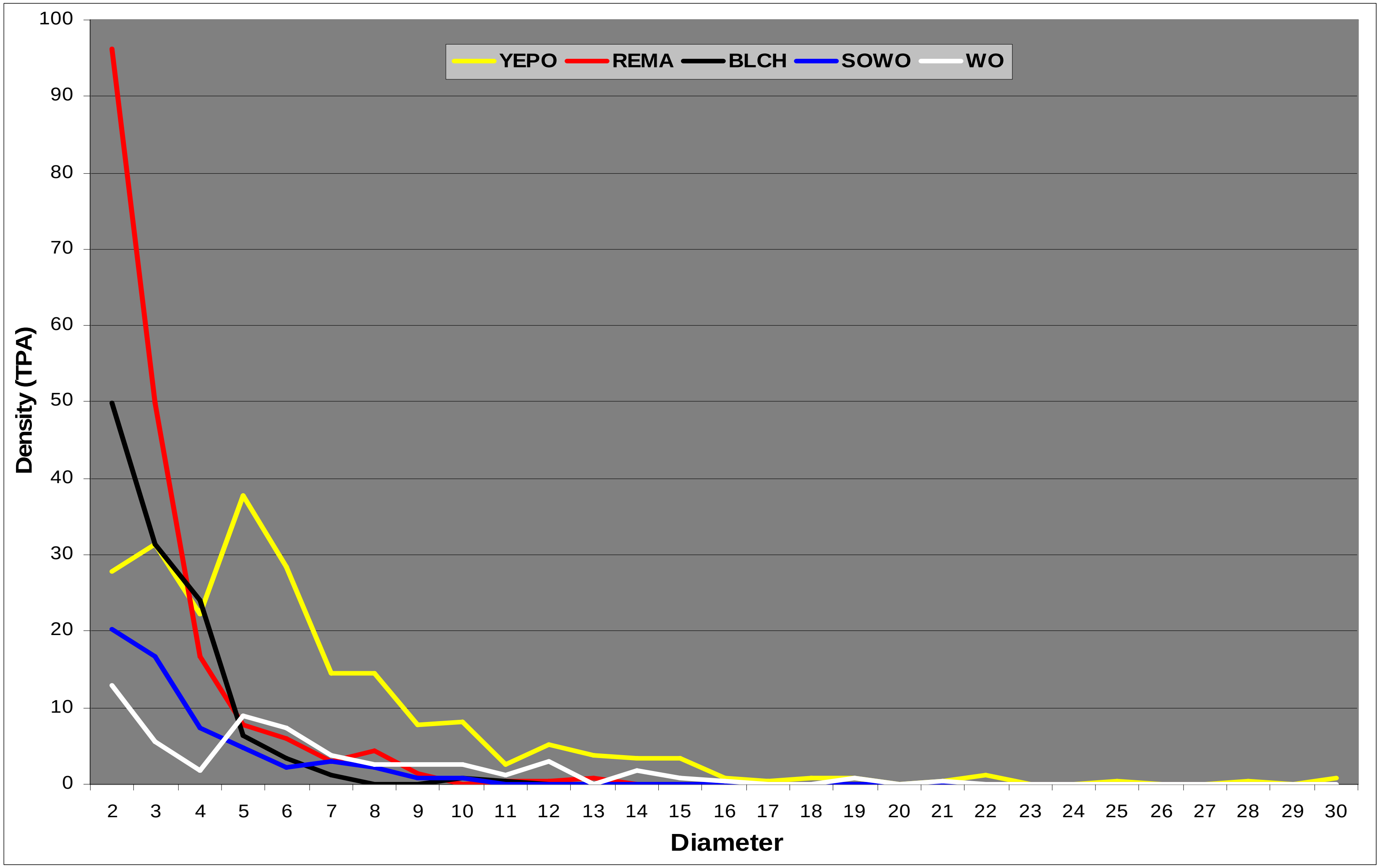
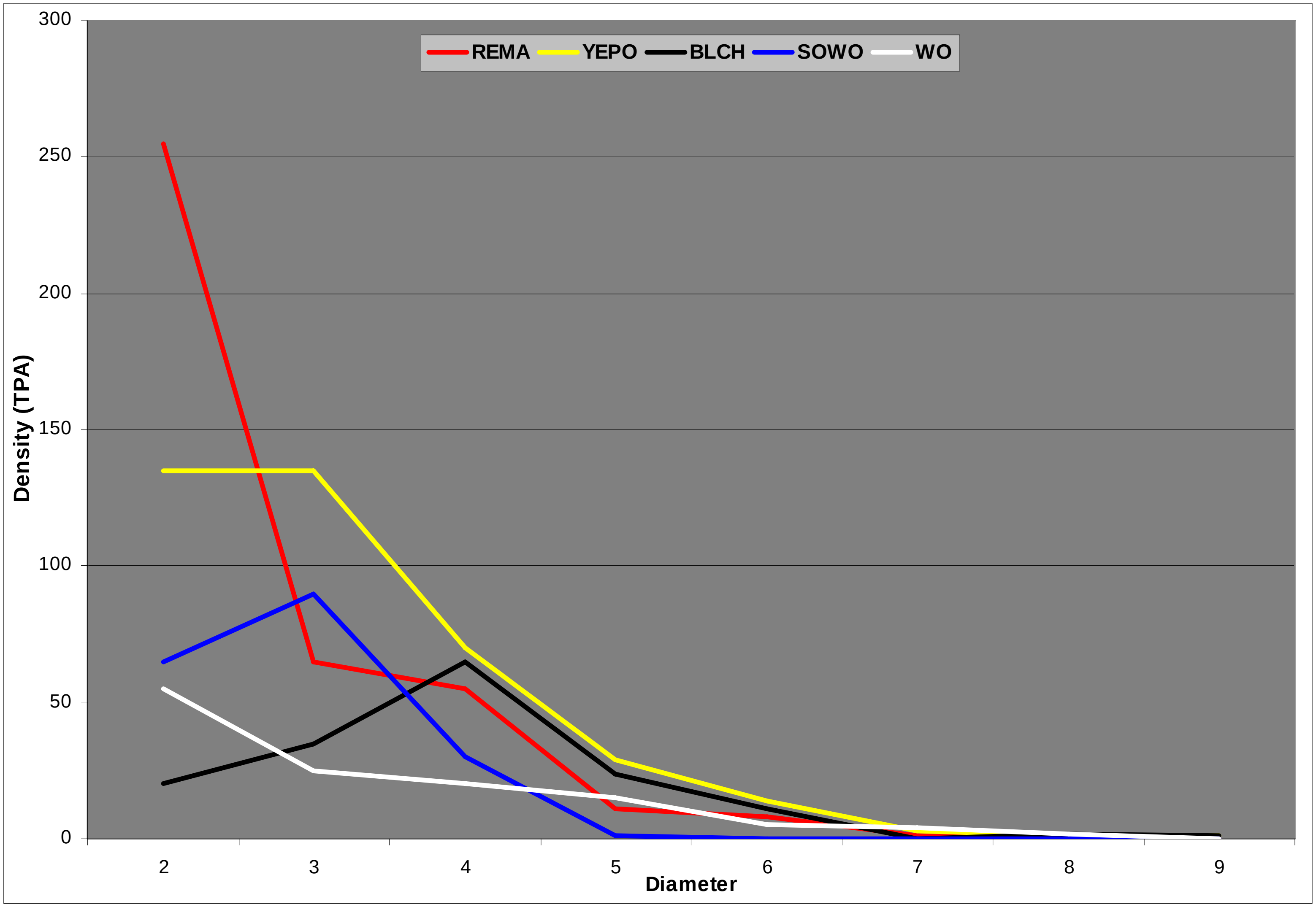


Figure 5.3 A and B: Diameter distribution curves for Tornado (A) and Clearcut (B) treatments based on density (trees per acre) and diameter at the FRREC in Oak Ridge, TN. Differing diameter ranges along the X-axis in each sub-figure (A and B) are based on the largest diameter tree round in the given treatment.

Figure 5.3-B.



REMA
YEPO
BLCH
SOWO
WO
300
250
200
150
100
50
0
Density (TPA)
2
3
4
5
6
7
8
9
Diameter

Table 5.3- A and B: Tree densities (trees per acre) by diameter class for Tornado (A) and Clearcut (B) disturbances at the FRREC in Oak Ridge, TN. Species reported vary for each treatment and are based on the species with the five greatest IV's for each treatment. See Appendix for species codes and names.

A.

DBH	**YEPO**	**REMA**	**BLCH**	**SOWO**	**WO**	**Total**
2	28	96	50	20	13	313
3	31	50	31	17	6	196
4	22	17	24	7	2	119
5	38	8	6	4.8	9	38
6	29	6	3.3	2.2	7	29
7	14	3.0	1.1	3.0	3.7	14
8	14	4.4	0	2.2	2.6	14
9	8	1.5	0	0.7	2.6	8
10	8	0	0.7	0.7	2.6	8
11	3	0.4	0.4	0	1.1	3
12	5	0.4	0	0	3.0	5
13	3.7	0.7	0	0	0	4
14	3.3	0	0	0	1.9	3
15	3.3	0	0	0	0.7	3
16	0.7	0	0	0	0.4	1
17	0.4	0	0	0	0	0
18	0.7	0	0	0	0	1
19	0.7	0	0	0	0.7	1
20	0	0	0	0	0	0
21	0.4	0	0	0	0.4	0
22	1.1	0	0	0	0	1
23	0	0	0	0	0	0
24	0	0	0	0	0	0
25	0.4	0	0	0	0	0
26	0	0	0	0	0	0
27	0	0	0	0	0	0
28	0.4	0	0	0	0	0
29	0	0	0	0	0	0
30	0.7	0	0	0	0	1
Total Density	216.3	187.0	117.4	58.1	56.3	763
Relative Density	28.4%	24.5%	15.4%	7.6%	7.4%	

B.

DBH	**REMA**	**YEPO**	**BLCH**	**SOWO**	**WO**	**Total**
2	255	135	20	65	55	560
3	65	135	35	90	25	425
4	55	70	65	30	20	245
5	11	29	24	1	15	87
6	8	14	11	0	5	41
7	1	3	0	0	4	10
8	0	1	2	0	2	7
9	0	1	1	0	0	2
Total Density	395	388	158	186	126	1377
Relative Density	28.7%	28.2%	11.5%	13.5%	9.2%	

Shannon Diversity

Tornado areas had higher species diversity than clearcut areas in the overstory and combined midstory/overstory strata while having lower diversity in the midstory and understory strata (Table 5.4). Differences in diversity were only significant in the overstory vegetation strata between treatments.

Non-metric Multidimensional Scaling

Based on species presence and absence, only herbaceous and understory woody < 4 ft. vegetation showed significant differences between tornado and clearcut areas. Two-dimensional representations of the NMDS scatter plot (Figure 5.4 A-E) show the low correlation between treatment plots.

As reported by the *R* values in Table 5.5, little treatment correlation exists between vegetation communities in the five different strata. Figures 5.4 A-E show the overlap of the clearcut and tornado treatments in the NMDS ordination. The herbaceous strata (Figure 5.4 A) had the greatest correlation value. Aside from the large number of points located at 0,0 on the plot, clearcut points tend to group away from tornado points. The woody < 4 ft. (Figure 5.4 B) strata had the second greatest correlation. In this plot, there is overlap between the two treatments, but clearcut blocks are grouped relatively tight. The woody > 4 ft. (Figure 5.4 C) had the lowest *R* value of all strata. It, like the herbaceous strata, had a high percentage of points at the 0,0 location of the x-axis and y-axis and had points of both treatments scattered throughout the plot. The midstory and overstory strata (Figures 5.4 D and E, respectively) show moderate correlations between treatment and

Table 5.4: Shannon H' values by treatment reported for each vegetation strata in the tornado disturbance treatments at the FRREC in Oak Ridge, TN. P-values are reported (signifies p ≤ 0.05).*

vegetation strata	**Tornado**	**Clearcut**	p-value
Understory > 4 ft.	0.663	0.788	0.6218
Midstory	1.337	1.475	0.1978
Overstory*	1.505	1.323	0.0144
Midstory/Overstory	1.785	1.646	0.4002

Table 5.5: Non-metric multidimensional scaling ANOSIM Global-R and p-values by vegetation strata for analysis for treatments and blocks at the FRREC in Oak Ridge, TN (signifies p ≤ 0.05).*

vegetation strata	R	p-value
Understory Herbaceous	0.181	0.004*
Understory Woody<4 ft.	0.14	0.001*
Understory Woody>4 ft.	0.006	0.38
Midstory	0.053	0.255
Overstory	0.124	0.076

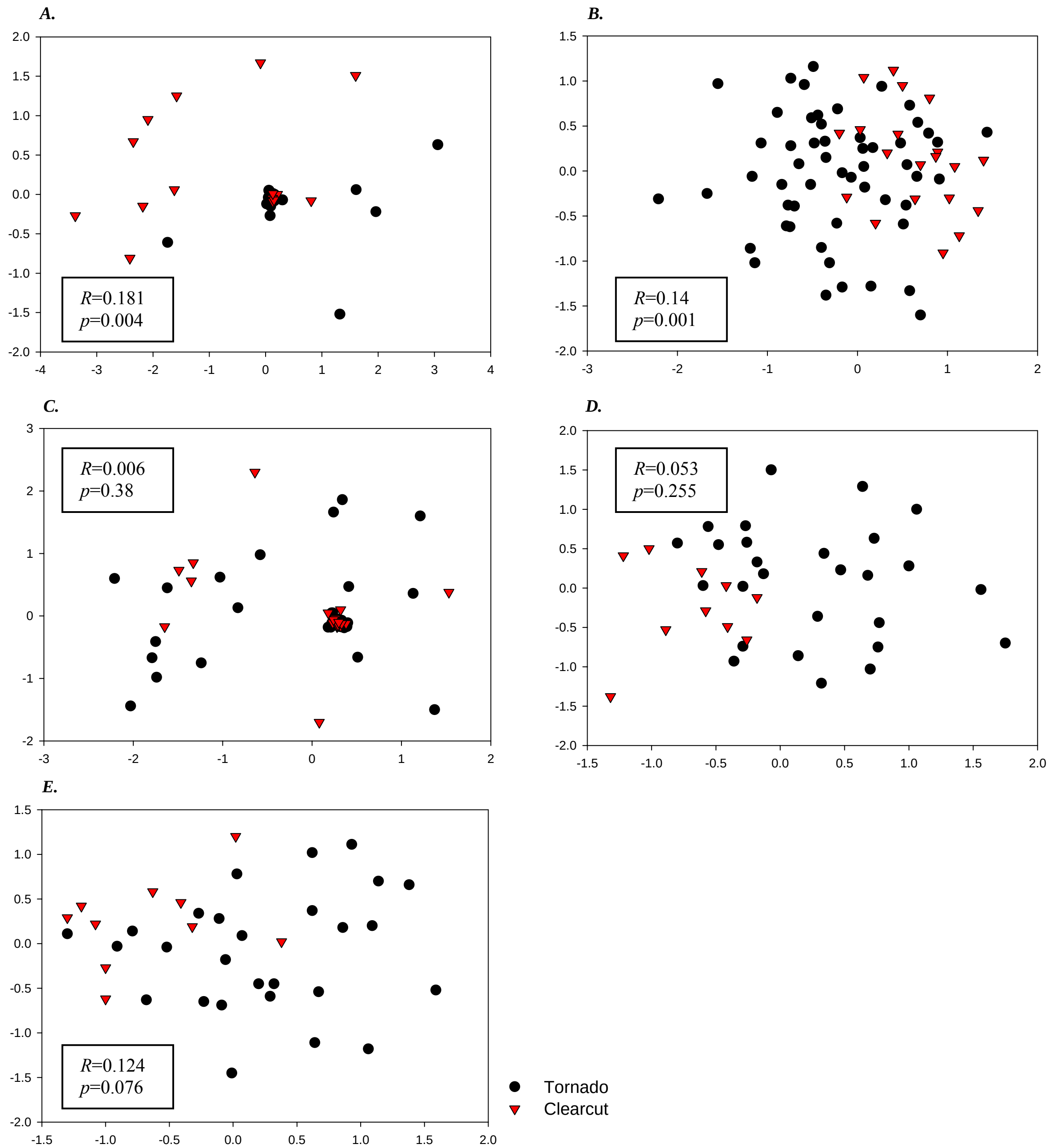


Figure 5.4 A-E: Non-metric multidimensional scaling X,Y scatter plot for five vegetation strata: Understory - herbaceous (A), Understory - woody vegetation < 4 ft. (B), Understory - woody vegetation > 4 ft. (C), Midstory (D), and Overstory (E) in the tornado disturbance treatments at the FRREC in Oak Ridge, TN. Scatter plots are separated by treatment and associated global R and p-values from the Analysis of Similarity (ANOSIM) are reported.

Table 5.6: Coarse woody debris volume (ft3/ac), density (logs/acre), and biomass (tons/ac) by treatment at the FRREC in Oak Ridge, TN. P-values are reported (signifies $p \leq 0.05$).*

CWD attribute	**Tornado**	**Clearcut**	p-value
Volume (ft^3/ac)*	635.9	155.2	0.0057
Density (logs/ac)*	108.1	42.4	0.0129
Biomass (tons/ac)*	0.666	0.089	0.0023

Coarse Woody Debris

Coarse woody debris volume, density, and biomass were all significantly different between treatments (Table 5.6). CWD volume was over 4 times greater in the tornado treatment. Similarly, CWD density was 2.5 times higher and CWD biomass was over 7 times greater in the tornado treatment compared to the clearcut treatment.

DISCUSSION

Species composition

Importance Values - Thirteen species had an IV greater than 4.0. The null hypothesis can only be rejected for three species: black gum, redbud, and sugar maple. All three of these species are considered to be shade tolerant and had significantly greater importance in the tornado areas compared to the clearcut areas. Black gum and sugar maple had an IV's almost six and twelve times greater, respectively, in the tornado area. Redbud was not detected in the clearcut areas and therefore had no importance value.

The comparison between tornado and clearcut disturbances expressed a relationship between the shade tolerance of the three significantly different species and the two different disturbance types. The clearcut was a stand initiating disturbance. The tornado was considered to be an incomplete stand-scale disturbance, though one of relatively high intensity, creating large canopy gaps and few widely-spaced residual trees. However, enough trees remained standing after the tornado disturbance to create light conditions significantly more suitable for shade tolerants like black gum, redbud, and sugar maple (Burns and Honkala 1990).

Since the tornado created light conditions more suitable for shade tolerant species, one would expect to see the inverse, where shade intolerant species were significantly more important in the clearcut areas. The IV's for many of the shade intolerant species (e.g. yellow-poplar, black cherry, and white oaks) (Burns and Honkala 1990) were much greater for both treatments than the shade tolerant species. Their relatively high density (Table 5.3) and importance indicate that light conditions were suitable for intolerant species to grow in both treatments. Therefore one can deduce that absence of shade, in conjunction with higher stem densities in the clearcut made it more difficult for shade tolerant species to compete. On the other hand, the few residual trees left in the tornado areas created more shade and lower stem densities, allowing shade tolerant species to remain as part of the species composition. Miller et al. (2006) supports the theory that residual trees have an effect on the amount of light reaching the forest floor and thus the species composition of the new cohort.

Non-metric Multidimensional Scaling - Results form the NMDS analysis suggest that the understory herbaceous vegetation and understory woody vegetation > 4 ft. were dissimilar between the clearcut and tornado areas. This response is likely due to the lack of species in the understory strata in the clearcut. The clearcut areas are in the stem exclusion stage of stand development. High stem densities create heavy shade in the understory causing little herbaceous or woody plant life to be able to survive (Oliver and Larson 1996).

Tree Density and Structure

No statistical analysis was conducted to test for treatment differences for diameter distribution and thus, density. Although the clearcut treatment was harvested almost four years before the tornado disturbance, total stem density is nearly two times greater in the clearcut areas. However, data in Table 5.3 showed that proportions of yellow-poplar, red maple, black cherry, and white oaks were similar across both treatments.

The greatest differences in stem density occurred in smaller diameter classes (Figure 5.2-A), where the clearcut had roughly twice the density of the tornado areas. In the 7-inch diameter class, tornado densities became greater than clearcut densities and continue to be greater for the remaining diameter classes. Tornado disturbance has been noted to provide a greater range of diameter classes compared to clearcut disturbances (Price et al. 1998). Similarly, no trees greater than 9 inches (22.9 cm) were measured in the clearcut areas, while tornado areas had a greater range of diameters, with the largest tree having a 33 inches (83.8 cm) diameter. Both treatments have negative exponential curves, but the tornado areas have more trees intermittently spaced in the larger diameter classes. Although sparse, the trees in the larger diameter classes are from the residual stand. Since the residual stand was two-aged, the tornado areas are now in the complex stage of development. The complex stage is reached when gaps created at different points in time result in a multi-aged stand (Oliver and Larson 1996). On the other hand, the clearcut areas are currently in the in the stem exclusion stage as the clearcut itself was a complete stand-initiating disturbance.

In both areas, red maple had similar diameter distribution, with high densities in the 2- and 3-inch classes, but quickly descending to the densities of the other five important species. Red maple has a tendency to vigorously stump sprout. Many of these sprouts would likely decrease in the stand in the near future as intraspecific competition causes mortality of smaller stems (Burns and Honkala 1990). Considering only the new cohort of trees, yellow-poplar had the highest densities in the remaining diameter classes. White oaks existed in relatively low densities in all but the larger diameter classes for each treatment.

The clearcut treatment showed vegetation results similar to the salvage/slash treatment in Chapter 4. The clearcut and salvage/slash had many of the same characteristics, such as density. Overall stem densities for the two treatments were 1,377 and 1,338 trees/acre, respectively, both relatively greater than other treatments in Chapter 4. Structurally both treatments were similar due to the lack of larger diameter trees left on site after their respective harvests.

Species Diversity

Differences in H' diversity was not detected in any of the strata except in the overstory; therefore the null hypothesis can be rejected for the overstory stratum. Here, the tornado areas had significantly greater diversity than the clearcut, due to a greater number of large diameter trees in the tornado and thus more tree species. This result was similar to that observed for the overstory strata of Chapter 4 when Shannon diversity was evaluated.

Coarse Woody Debris

The tornado treatment had significantly greater CWD volume, density and biomass; hence the null hypothesis can be rejected for all three attributes. In the tornado areas, there was more than four times the CWD volume, more than two times the CWD density, and more than seven times the CWD biomass. Much of the fine woody debris in the clearcut has decayed since the time of harvest and most of the large or coarse woody debris (CWD) was removed at part of the harvest prescription. Pole stands (the category the clearcut treatment is most comparable to) tend to have lowest CWD loads of all the even-aged developmental stages (McCarthy and Bailey 1993), due to the lack of large CWD pieces left after harvest (Price et al. 1998).

The nature of each disturbance, led me to expect that there would be more CWD loads in the tornado area, which was supported by the data. Clearcut CWD attributes resemble the salvage treatment from Chapter 4. Both CWD volume (155.2 and 157 ft^3/acre, respectively) and CWD biomass (0.089 and 0.073 tons/acre) were similar between these two treatments. Although the harvests between the clearcut and salvage/slash were similar (removing to the 2-inch (5.1 cm) diameter class), small diameter trees were removed from the clearcut to allow for the planting of pines. Similar CWD characteristics were seen in the salvage treatment only because those low diameter trees were left standing.

Management Implications

As the value of forest management becomes more recognized as an integral part of ecosystem management, there is a heightened interest in how silviculture can be used to emulate natural disturbances. Data from this study indicate that clearcuts and tornados are structurally two different disturbances. Although species importance and relative density are similar in both treatments, the tornado area is more structurally diverse. Overall, diameter distributions had greater ranges and coarse woody debris loading was greater in the tornado areas.

If silvicultural methods are used to imitate natural disturbance, a more irregular and erratic marking prescription is needed to ensure leaving residual trees that will have similar effects as the residual trees in the tornado areas. Diameter distributions and field observations for the tornado area show that trees from all crown classes must be left to imitate such conditions. Furthermore, to emulate the CWD loads from a tornado disturbance, some downed trees of all sizes would need to left on site.

From a timber management perspective, lower stem densities seen in the tornado areas will likely result in shorter, lower-grade trees because early competition played less of a part in individual tree growth (Clatterbuck and Hodges 1987). Although relative densities and IV's for individual species are similar, density-related competition occurs to a lesser extent in the tornado areas.

Research Implications

Some level of warning should be given along with the results in this chapter. As discussed in Chapter 4, the tornado areas had high levels of variability in them due to the nature of wind disturbances. Silvicultural clearcuts however, tended to have less variability associated with them because such a disturbance is fairly constant across the stand.

As discussed in the Methods of this chapter, vegetation measurements were conducted in the same manner at each plot location for both treatments. However, the number of plots and plot layout was different for each treatment because of the small area of the silvicultural clearcut areas from the mixed-pine hardwood study (Andrews 1995). The low number of plots from the clearcut treatment compared to tornado area, in conjunction with the variability in the tornado treatment may have increased the chances making Type II error. For instance, Table 5.1 indicated a difference of almost 20 between treatments of yellow-poplar IV's. The theories behind stand dynamics would indicate that yellow-poplar should have more success in a complete stand initiating disturbance such as a clearcut versus an incomplete disturbance such as a tornado, yet no significant differences were detected.

Conversely, the aforementioned difficulties in experimental design should strengthen the importance of detected differences. This is especially true in the vegetation stand characteristics (i.e. IV's, Shannon H', and NMDS), where both low number of clearcut plots and tornado treatment variability could have hidden stand differences. For this reason, the dissimilarities discovered between these two treatments signify that differences are apparent for those stand characteristics.

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APPENDIX:

Species Codes for Importance Values Analysis and All Species Identified in Study Area

Appendix A-1: Species codes and common and scientific names for tree species used in Importance Value analysis for the tornado-disturbance study at the FRREC in Oak Ridge, TN.

Species Code	***Common Name***	***Scientific Name***
BLCH	Black cherry	*Prunus serotina*
BLGU	Black gum	*Nyssa sylvatica*
DOWO	Flowering dogwood	*Cornus florida*
Elms	Elms spp.	*Ulmus spp.*
HICK	Hickory spp.	*Carya spp.*
REBU	Redbud	*Cercis canadensis*
Red Oaks (RO)	Red oak group	*Quercus spp.*
REMA	Red maple	*Acer rubrum*
SASS	Sassafras	*Sassafras albidum*
SMSU	Smooth sumac	*Rhus glabra*
SOWO	Sourwood	*Oxydendrum arboreum*
SUMA	Sugar maple	*Acer saccharum*
SWGU	Sweetgum	*Liquidambar styraciflua*
VIPI	Virginia pine	*Pinus virginiana*
White Oaks (WO)	White oak group	*Quercus spp.*
WHPI	Eastern white pine	*Pinus strobus*
YEPO	Yellow-poplar	*Liriodendron tulipifera*

Appendix A-2: Herbaceous species recorded during data collection for the tornado-disturbance study at the FRREC in Oak Ridge, TN.

Code	*Common name*	*Scientific name*
ACAL	White baneberry	*Actea alba*
ASCA	Wild ginger	*Asarum canadense*
ASSP	Aster	*Aster spp.*
BODI	Common grapefern	*Botychrium dissectum*
CARX	Sedge	*Carex spp.*
CIRA	Black cohosh	*Cimicifuga racemosa*
CRCA	Honewort	*Cryptotaenia canadensis*
DESP	Desmodium	*Desmodium spp.*
DICH	Dichanthelium	*Dichanthelium spp.*
ELCA	Carolina elephant's foot	*Elephantopus carolinianus*
FRVI	Virginia strawberry	*Fragaria virginiana*
GAAP	Cleavers	*Galium aparine*
GACI	White wild licorice	*Galium circaezans*
GEUM	Avens	*Geum spp.*
GOPU	Downy rattlesnake-plantain	*Goodyera pubescens*
HEAM	Round-lobed hepatica	*Hepatica americana*
HISC	Rough hawkweed	*Hieracium scabrum*
IPSP	Morning glory	*Ipomoea spp.*
IRVE	Dwarf iris	*Iris verna*
LYDI	Fan clubmoss	*Lycopodium digitatum*
MIVI	Japanese stilt grass	*Microstegium vimineum*
OXST	Yellow wood-sorrel	*Oxalis stricta*
PEFR	Beefsteak plant	*Perilla fruitescens*
POAC	Christmas fern	*Polystichum acrostichoides*
POBI	Solomon's seal	*Polygonatum biflorum*
PONO	Rough cinquefoil	*Potentilla norvegica*
POVI	Virginia knotweed	*Polygonum virginianum*
RUCA	Carolina wild plum	*Ruellia caroliniensis*
SATR	Snakeroot	*Sanicula trifoliata*
SCEL	Hairy skullcap	*Scutellaria elliptica*
SOCA	Horse nettle	*Solanum carolinese*
SOSP	Goldenrod spp.	*Solidago spp.*
TICO	Foamflower	*Tiarella cordifolia*
VEOC	Crown-beard	*Verbesina occidentalis*
VISP	Violet	*Viola spp.*

Appendix A-3: Woody species less than 4 feet (1.2M) tall recorded during data collection for the tornado-disturbance study at the FRREC in Oak Ridge, TN.

Code	*Common name*	*Scientific name*
AMBE	American beech	*Fagus grandifolia*
BLCH	Black cherry	*Prunus serotina*
BLGU	Blackgum	*Nyssa silvatica*
CABU	Carolina buckthorn	*Rhamnus caroliniana*
CHIN	Chinkapin oak	*Quercus muhlenbergii*
CHOA	Chestnut oak	*Quercus prinus*
CHPR	Chinese privet	*Ligustrum sinense*
CROSS	Crossvine	*Bignonia capreolata*
DEDA	Devil's darning needles	*Clametis virginiana*
DOWO	Flowering dogwood	*Cornus florida*
ERCE	Eastern red cedar	*Juniperus virginiana*
FOGR	Fox grape	*Vitis labrusca*
GOOS	Gooseberry	*Ribes spp.*
GRNU	Groundnut	*Apios americana*
GRSP	Grape spp.	*Vitis spp.*
HACK	Hackberry	*Celtis occidentalis*
HIBL	Highbush blueberry	*Vaccinium corymbosum*
HICK	Hickory	*Carya spp.*
HOPE	Hog peanut	*Amphicarpaea bracteata*
IRON	Ironwood	*Ostrya virginiana*
JAHO	Japanese honeysuckle	*Lonicera japonica*
MAVI	Maple-leaf viburnum	*Viburnum acerifolium*
MIMO	Mimosa	*Albizia julibrissin*
MUSC	Musclewood	*Carpinus caroliniana*
NROA	Northern red oak	*Quercus rubra*
PAPA	Paw-paw	*Asimina triloba*
PERS	Persimmon	*Diospyrus virginiana*
PEVI	Peppervine	*Ampelopsis arborea*
POIV	Poison ivy	*Toxicodendron radicans*
REBU	Redbud	*Cercis canadensis*
REEL	Red elm	*Ulmus rubra*
REMA	Red maple	*Acer rubrum*
REMU	Red mulberry	*Morus rubra*
RIGR	River grape	*Vitis amurensis*
ROSP	Rose spp.	*Rosa sp.*
RUSP	Rubus spp.	*Rubus sp.*
SASS	Sassafras	*Sassafras albidum*
SEBE	Serviceberry	*Amelanchier spp.*
SMBN	Smilax bona-nox	*Smilax bona-nox*
SMGL	Smilax glauca	*Smilax glauca*
SMRO	Smilax rotundifolia	*Smilax rotundifolia*
SPBU	Spicebush	*Lindera benzoin*
SPWI	Spotted wintergreen	*Chimaphila maculata*
STBU	Strawberry bush	*Euonymus americanus*
SUMA	Sugar maple	*Acer saccharum*
SWGU	Sweetgum	*Lquidambar styraciflua*

Code	*Common name*	*Scientific name*
ULSP	Ulmus spp.	*Ulmus spp.*
VICR	Virginia creeper	*Parthenocissus quinquefolia*
VIPI	Virginia pine	*Pinus virginiana*
VISP	Viburnum spp.	*Viburnum spp.*
WHOA	White oak	*Quercus alba*
WHPI	White pine	*Pinus strobus*
WIEL	Winged elm	*Ulmus alata*
WIYA	Wild yam	*Dioscorea villosa*
YEPO	Yellow-poplar	*Liriodendron tulipifera*

Appendix A-4: Woody species greater than 4 feet (1.2M) tall recorded during data collection for the tornado-disturbance study at the FRREC in Oak Ridge, TN.

Code	*Common name*	*Scientific name*
AMBE	American beech	*Fagus grandifolia*
ASHX	Ash	*Fraxinus spp.*
BLCH	Black cherry	*Prunus serotina*
BLGU	Blackgum	*Nyssa sylvatica*
CABU	Carolia buckthorn	*Rhamnus caroliniana*
CHIN	Chinkapin oak	*Quercus muhlenbergii*
CHOA	Chestnut oak	*Quercus prinus*
CUMA	Cucumber magnolia	*Magnolia acuminata*
DOWO	Flowering dogwood	*Cornus florida*
ERCE	Eastern red cedar	*Juniperus virginiana*
GOOS	Gooseberry	*Ribes spp.*
HICK	Hickory spp.	*Caraya spp.*
IRON	Ironwood	*Ostrya virginiana*
MUSC	Musclewood	*Carpinus caroliniana*
NROA	Northern red oak	*Quercus rubra*
REBU	Redbud	*Cercis canadensis*
REEL	Red elm	*Ulmus rubra*
REMA	Red maple	*Acer rubrum*
REMU	Red mulberry	*Morus rubra*
SASS	Sassafras	*Sassafras albidum*
SERV	Serviceberry	*Amelanchier spp.*
SMSU	Smooth sumac	*Rhus glabra*
STBU	Strawberry bush	*Euonymus americanus*
SUMA	Sugar Maple	*Acer saccharum*
SWGU	Sweetgum	*Liquidambar styraciflua*
VIPI	Virginia pine	*Pinus virginiana*
WHOA	White oak	*Quercus alba*
WHPI	White pine	*Pinus stobus*
WIEL	Winged elm	*Ulmus alata*
YEPO	Yellow-poplar	*Liriodendron tulipifera*

Appendix A-5: Woody midstory and overstory recorded during data collection for the tornado-disturbance study at the FRREC in Oak Ridge, TN.

Code	*Common name*	*Scientific name*
AILA	Ailanthus	*Ailanthus altisima*
AMBA	American basswood	*Tilia americana*
AMBE	American beech	*Fagus grandifolia*
AMEL	American elm	*Ulmus americana*
AMSY	American sycamore	*Platanus occidentalis*
ASHX	Green/White ash	*Fraxinus spp.*
AUOL	Autumn olive	*Elaeagnus umbellata*
BLCH	Black cherry	*Prunus serotina*
BLGU	Black gum	*Nyssa sylvatica*
BLOA	Black oak	*Quercus velutina*
BLWA	Black walnut	*Juglans nigra*
CHIN	Chinquapin oak	*Quercus muhlenbergii*
CHOA	Chestnut oak	*Quercus prinus*
DOWO	Flowering dogwood	*Cornus florida*
ERCE	Eastern redcedar	*Juniperus virginiana*
HACK	Hackberry	*Celtis occidentalis*
HAWT	Hawthorn	*Crataegus spp.*
HICK	Hickory spp.	*Carya spp.*
IRON	Ironwood	*Ostrya virginiana*
LOPI	Loblolly pine	*Pinus taeda*
MIMO	Mimosa	*Albizia julibrissin*
MUSC	Musclewood	*Carpinus caoliniana*
NROA	Northern red oak	*Quercus rubra*
PERS	Persimmon	*Diospyrus virginiana*
PRTR	Princess tree	*Paulownia tomentosa*
REBU	Redbud	*Cercis canadensis*
REEL	Red elm	*Ulmus rubra*
REMA	Red maple	*Acer rubrum*
REMU	Red mulberry	*Morus rubra*
SASS	Sassafras	*Sassafras albidum*
SCOA	Scarlet oak	*Quercus coccinea*
SMSU	Smooth sumac	*Rhus glabra*
SOWO	Sourwood	*Oxydendrum arboreum*
SUMA	Sugar maple	*Acer saccharum*
SWGU	Sweetgum	*Liquidambar styraciflua*
UMMA	Umbrella magnolia	*Magnolia tripetala*
VIPI	Virginia pine	*Pinus virginiana*
WHOA	White oak	*Quecus alba*
WHPI	White pine	*Pinus strobus*
WIEL	Winged elm	*Ulmus alata*
YEPO	Yellow-poplar	*Liriodendron tulipifera*

VITA

Jonathan McGrath was born in Youngstown, OH in 1984. He was raised in New Wilmington, PA where he gained an appreciation for the outdoors by hunting and fishing the lands of western Pennsylvania with his father and friends. Jonathan graduated from Wilmington Area High School in 2002. He then went on to study at The Pennsylvania State University and graduated with a Bachelor's of Science in Forest Management in 2006.

Jonathan's work experience includes both the private and public sectors of forestry. In January of 2007 he began his master's research working under Dr. Wayne Clatterbuck. These experiences have focused his professional interests in silviculture, forest stand dynamics, and habitat management.